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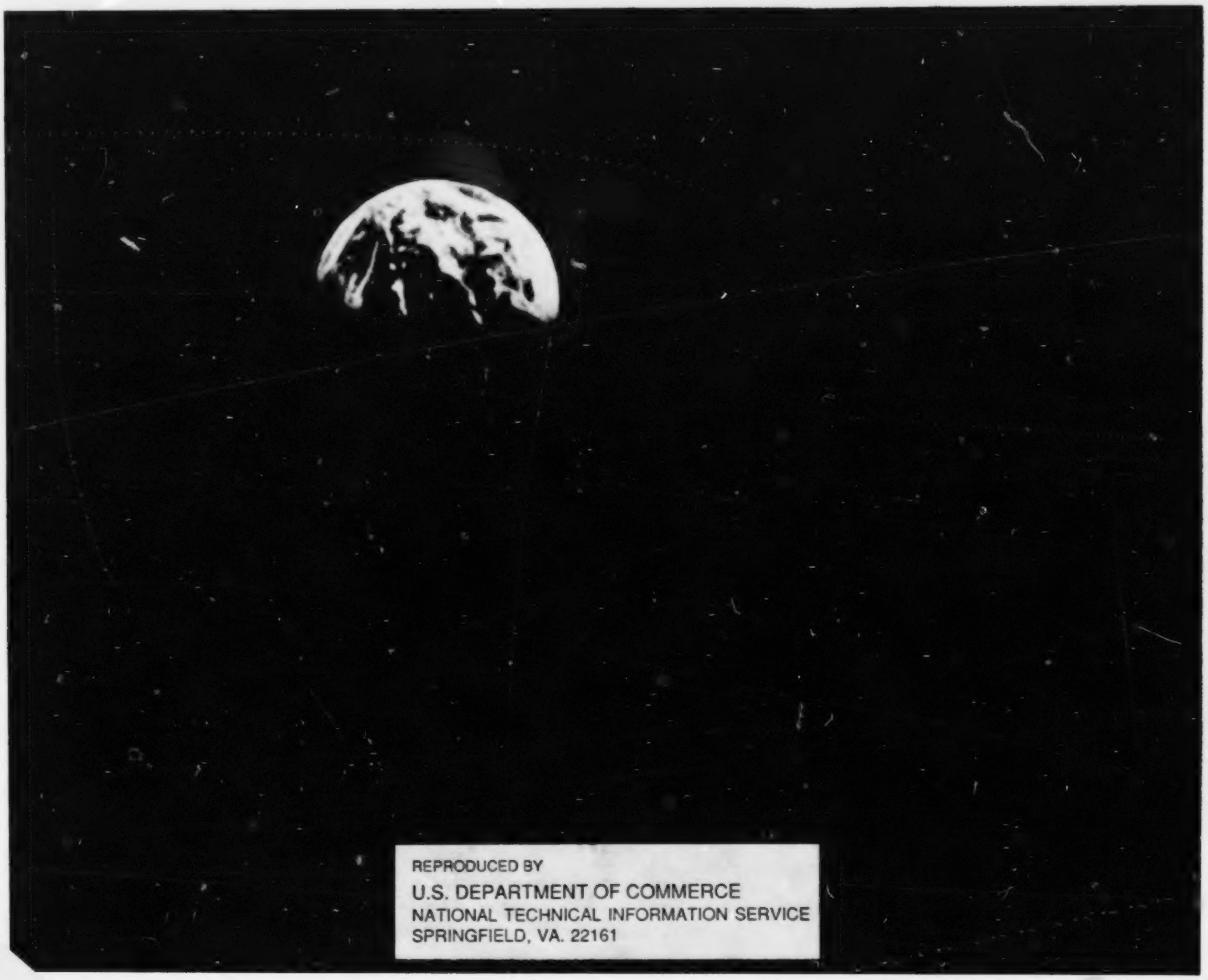

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THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES:

APPENDIX H - INFRASTRUCTURE

Editors: Joel B. Smith and Dennis A. Tirpak

OFFICE OF POLICY, PLANNING AND EVALUATION
U.S. ENVIRONMENTAL PROTECTION AGENCY
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PREFACE

The ecological and economic implications of the greenhouse effect have been the subject of discussion within the scientific community for the past three decades. In recent years, members of Congress have held hearings on the greenhouse effect and have begun to examine its implications for public policy. This interest was accentuated during a series of hearings held in June 1986 by the Subcommittee on Pollution of the Senate Environment and Public Works Committee. Following the hearings, committee members sent a formal request to the EPA Administrator, asking the Agency to undertake two studies on climate change due to the greenhouse effect.

> One of the studies we are requesting should examine the potential health and environmental effects of climate change. This study should include, but not be limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, and estuaries, as well as other ecosystems and societal impacts. This study should be designed to include original analyses, to identify and fill in where important research gaps exist, and to solicit the opinions of knowledgeable people throughout the country through a process of public hearings and meetings.

To meet this request, EPA produced the report entitled ***The Potential Effects of Global Climate Change on the United States***. For that report, EPA commissioned fifty-five studies by academic and government scientists on the potential effects of global climate change. Each study was reviewed by at least two peer reviewers. The Effects Report summarizes the results of all of those studies. The complete results of each study are contained in Appendices A through J.

Appendix	**Subject**
A	Water Resources
B	Sea Level Rise
C	Agriculture
D	Forests
E	Aquatic Resources
F	Air Quality
G	Health
H	Infrastructure
I	Variability
J	Policy

GOAL

The goal of the Effects Report was to try to give a sense of the possible direction of changes from a global warming as well as a sense of the magnitude. Specifically, we examined the following issues:

- sensitivities of systems to changes in climate (since we cannot predict regional climate change, we can only identify sensitivities to changes in climate factors)
- the range of effects under different warming scenarios
- regional differences among effects
- interactions among effects on a regional level

- national effects
- uncertainties
- policy implications
- research needs

The four regions chosen for the studies were California, the Great Lakes, the Southeast, and the Great Plains. Many studies focused on impacts in a single region, while others examined potential impacts on a national scale.

SCENARIOS USED FOR THE EFFECTS REPORT STUDIES

The Effects Report studies used several scenarios to examine the sensitivities of various systems to changes in climate. The scenarios used are plausible sets of circumstances although none of them should be considered to be predictions of regional climate change. The most common scenario used was the doubled CO_2 scenario ($2XCO_2$), which examined the effects of climate under a doubling of atmospheric carbon dioxide concentrations. This doubling is estimated to raise average global temperatures by 1.5 to 4.5°C by the latter half of the 21st century. Transient scenarios, which estimate how climate may change over time in response to a steady increase in greenhouse gases, were also used. In addition, analog scenarios of past warm periods, such as the 1930s, were used.

The scenarios combined average monthly climate change estimates for regional grid boxes from General Circulation Models (GCMs) with 1951-80 climate observations from sites in the respective grid boxes. GCMs are dynamic models that simulate the physical processes of the atmosphere and oceans to estimate global climate under different conditions, such as increasing concentrations of greenhouse gases (e.g., $2XCO_2$).

The scenarios and GCMs used in the studies have certain limitations. The scenarios used for the studies assume that temporal and spatial variability do not change from current conditions. The first of two major limitations related to the GCMs is their low spatial resolution. GCMs use rather large grid boxes where climate is averaged for the whole grid box, while in fact climate may be quite variable within a grid box. The second limitation is the simplified way that GCMs treat physical factors such as clouds, oceans, albedo, and land surface hydrology. Because of these limitations, GCMs often disagree with each other on estimates of regional climate change (as well as the magnitude of global changes) and should not be considered to be predictions.

To obtain a range of scenarios, EPA asked the researchers to use output from the following GCMs:

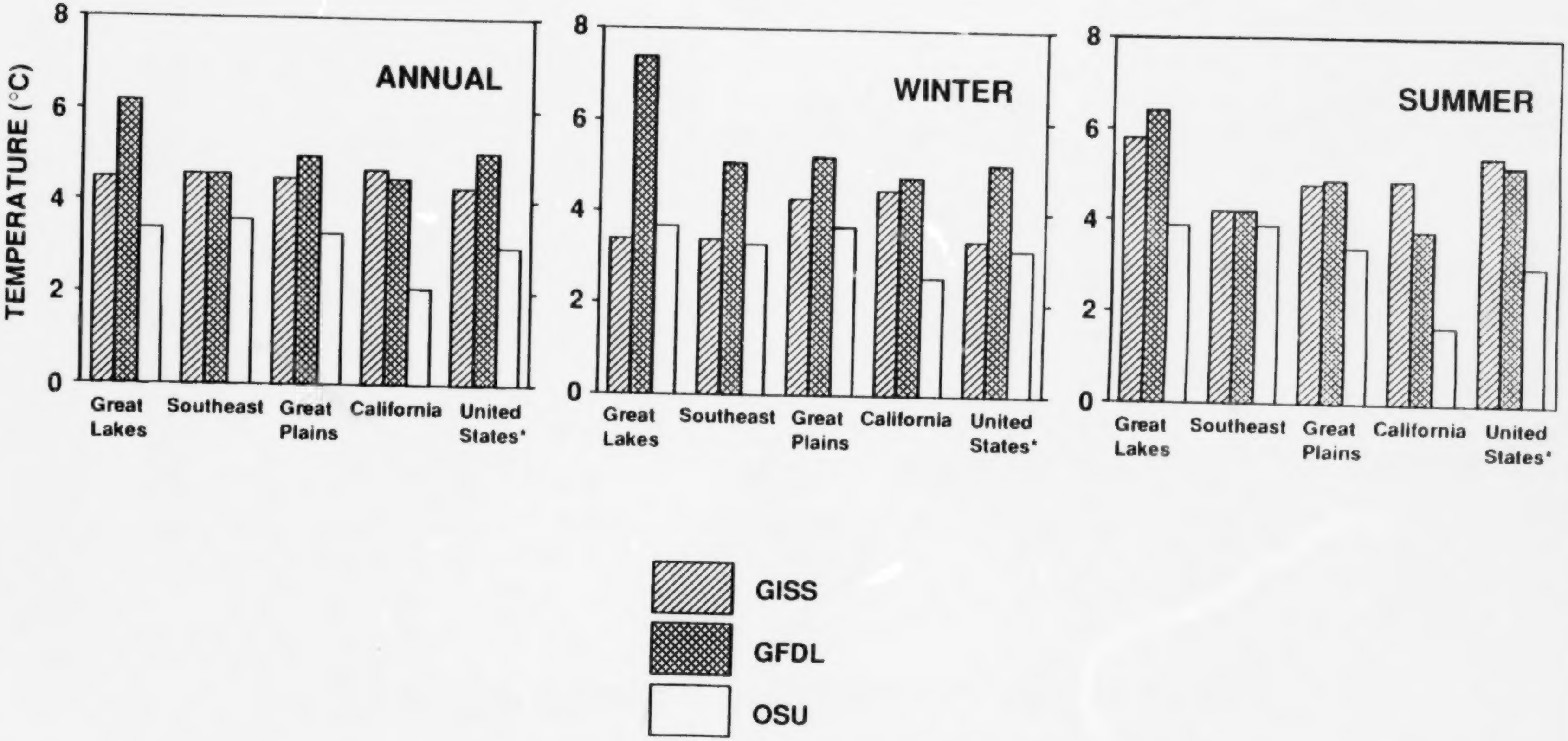
- Goddard Institute for Space Studies (GISS)
- Geophysical Fluid Dynamics Laboratory (GFDL)
- Oregon State University (OSU)

Figure 1 shows the temperature change from current climate to a climate with a doubling of CO_2 levels, as modeled by the three GCMs. The figure includes the GCM estimates for the four regions. Precipitation changes are shown in Figure 2. Note the disagreement in the GCM estimates concerning the direction of change of regional and seasonal precipitation and the agreement concerning increasing temperatures.

Two transient scenarios from the GISS model were also used, and the average decadal temperature changes are shown in Figure 3.

FIGURE 1. TEMPERATURE SCENARIOS

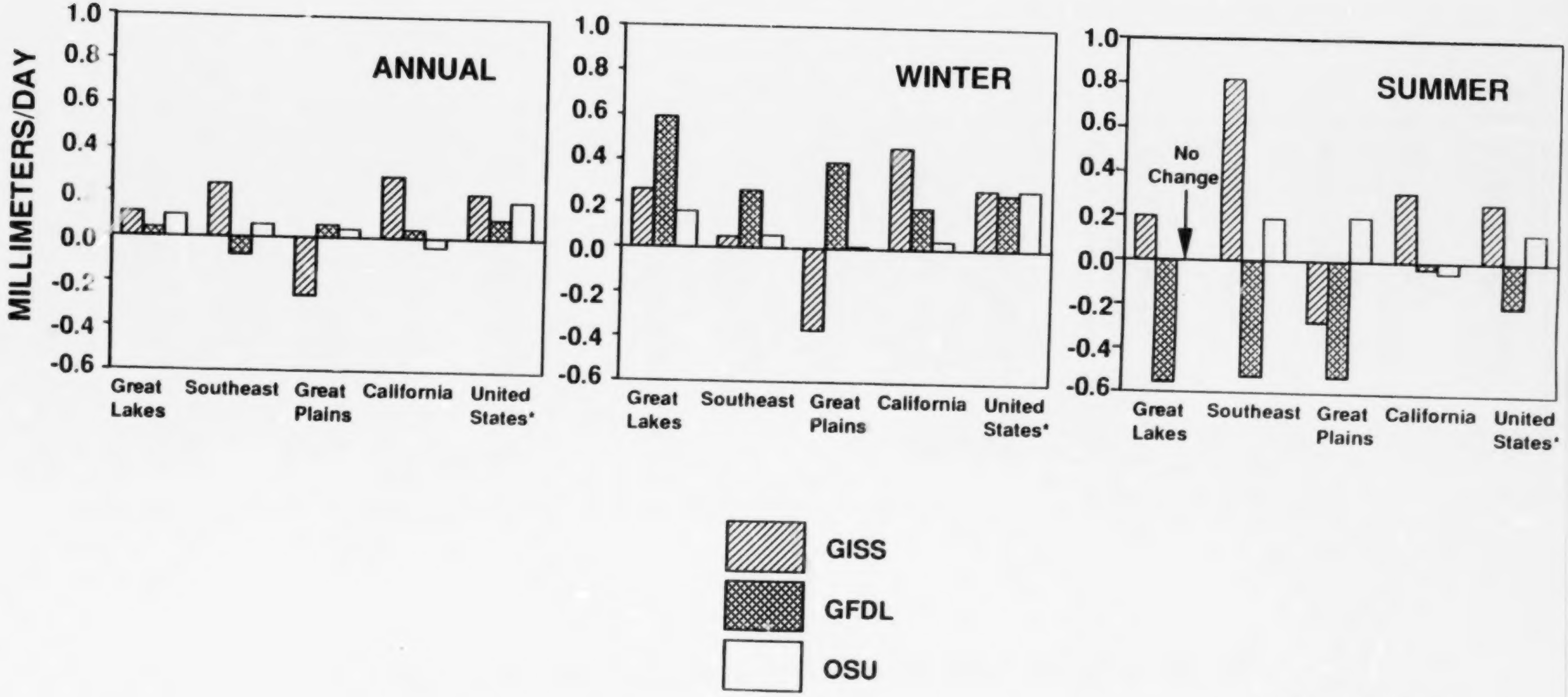
GCM Estimated Change in Temperature from $1xCO_2$ to $2xCO_2$



* Lower 48 States

FIGURE 2. PRECIPITATION SCENARIOS

GCM Estimated Change in Precipitation from $1xCO_2$ to $2xCO_2$



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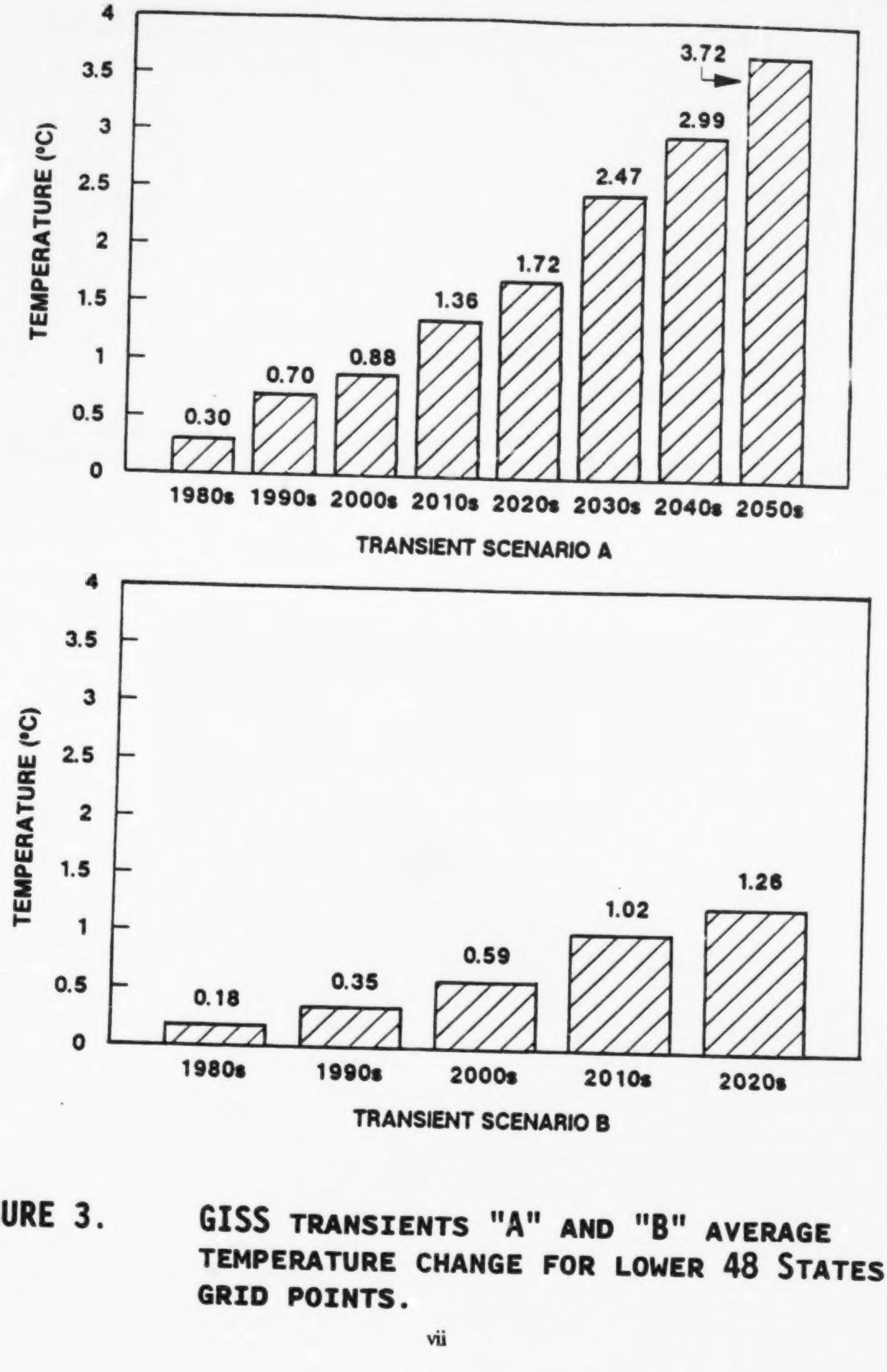

FIGURE 3. GISS TRANSIENTS "A" AND "B" AVERAGE TEMPERATURE CHANGE FOR LOWER 48 STATES GRID POINTS.

THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON REGIONAL AND NATIONAL DEMANDS FOR ELECTRICITY

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Contract No. 68-01-7033

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FINDINGS[1]

Global warming in response to increased atmospheric concentrations of "greenhouse gases" could affect electric utilities through several different pathways. One of the most critical impact pathways is likely to be the demand for electricity because of the importance of weather-sensitive demands in determining (1) the amount of generating capacity a utility must build and maintain to meet its customers' demands reliably and (2) the most efficient ways of utilizing the utility's resources. These determinations are important to the utility industry because of its capital-intensivity and its long planning horizon; uncertainty in future demands associated with potential changes in climate may pose substantial economic risks to the industry.

A study was conducted to estimate the potential impacts of greenhouse gas-induced temperature changes on U.S. regional and national demands for electricity, and the implications of these changes in demands for utility planning and operations. The study is an extension of an earlier analysis of two case study utility systems performed by ICF Incorporated. In the current study, climate change impacts are estimated for aggregations of utility systems in the Great Lakes, the Southeast, the Southern Great Plains, California, and the United States as a whole. Impacts are measured in terms of changes in utility peak demands and annual energy requirements, generating capacity requirements, electricity generation and fuel use, and capital and operating costs.

The steps in the analysis can be summarized as follows. First, two alternative climate change scenarios were developed for 47 state and sub-state utility regions. The climate change scenarios are based upon the results of two "transient experiments" developed by the Goddard Institute of Space Sciences (GISS) using a general circulation model of the Earth's atmosphere. The experiments differ primarily in the assumed atmospheric concentrations of greenhouse gases and the degree of volcanic activity. They are designated as "GISS A" and "GISS B." For purposes of this analysis, only changes in monthly mean temperatures from GISS A and GISS B were used to characterize future climate changes. Climate change scenarios were developed using both GISS A and GISS B for 2010, and using only GISS A for 2055.

Second, the weather-sensitivities of demands for electricity were estimated based upon findings of the case studies and analyses of historic temperature and demand data performed by individual utilities. Estimated parameters relating changes in temperature to changes in peak demand and annual energy requirements were developed from these sources. It was assumed that these relationships based upon analysis of historic data would continue into the future and would be valid over the range of temperature changes estimated in the GISS transient experiments (3.4-5.0 degrees C average annual increases in GISS A by the 2050s). Because of several uncertainties associated with the estimation of the weather-sensitivity parameters, an alternative set of values also was used in the analysis. The alternative increased the estimated weather-sensitivities by 50%.

Third, the results of these steps were combined to estimate changes in demands for electricity in 2010 and 2055 under the alternative climate change and weather-sensitivity assumptions. Estimated increases in peak demand on a national basis ranged from 2 to 6% in 2010, with substantial variation around these results on a regional basis. Changes in national annual energy requirements in 2010 were more modest, ranging from 1 to 2%. In 2055, peak demands nationally were estimated to increase by 13 - 20% and annual energy requirements by 4 - 6%.

Then, these results and a set of utility planning assumptions were used as inputs to a model that simulates utility resource planning and operations. The model was used to evaluate the implications of the changes in demand induced by climate change for generating capacity requirements, generation and fuel use, and electricity production costs. Climate change impacts were estimated by comparing (1) the planning model outputs assuming climate change occurs with (2) "base case" outputs assuming no climate change occurs. In addition to uncertainty being represented by alternative climate change scenarios and alternative weather-sensitivity parameter estimates, the rate of growth in base case electricity demands was varied, corresponding to alternative GNP growth rate assumptions.

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[1] Although the information in this report has been funded wholly by the U.S. Environmental Protection Agency under Contract No. 68-01-7033, Work Assignment No. 225, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

Some of the results of the analysis are summarized in Figure S-1 and Figure S-2. Figure S-1 presents the estimated national impacts of changes in electricity demand induced by long-term temperature change on new generating capacity requirements (in gigawatts) and on electricity generation (in billions of kilowatt-hours). In 2010, new capacity requirements induced by climate change increase by 9-19%, or about 25 to 55 GW. The majority of the capacity increase is for peaking capacity as opposed to baseload capacity. This is a significant finding, representing an average increase of up to 1 GW per state.[2] The investment associated with these capacity increases is several billion dollars (in constant 1986 $). By 2055, the change in new capacity requirements increases in percentage terms and represents several hundred gigawatts. Under high GNP growth and high weather-sensitivity assumptions, the estimated increase due to climate change is almost 400 GW.

Annual generation increases are not quite as large in percentage terms, but nonetheless account for several hundred billion kilowatt-hours by 2055. Annual fuel and O&M costs associated with these increases in generation are hundreds of millions of dollars in 2010 and billions of dollars by 2055.

Figure S-2 presents some of the regional results. The figure indicates new capacity requirements in 2055 under (higher growth) base case conditions and under the higher weather-sensitivity climate change assumptions. The impacts range from an increase of about 20 GW in California to over 100 GW in the Southeast. As a percentage of base case demand, the results are particularly significant for the Southeast and the Southern Great Plains. In fact, the potential climate change impacts estimated for these two regions are similar in magnitude to the range of base case demand growth uncertainty represented by the alternative GNP assumptions.

There are several important uncertainties and limitations to the analysis that should be kept in mind when interpreting these results. Because of these uncertainties and limitations, the cases analyzed have been referred to as "scenarios," and the results should not be considered as "projections" or "forecasts." Among the key uncertainties and limitations are:

o A narrow focus on impact pathways, considering only the potential effects of temperature change on changes in electricity demand. Greenhouse gas-induced changes in temperature and other climate variables could affect many other aspects of utility planning and operations.

o Limited availability of climate change information (e.g., variations in temperature changes and occurrence of extreme events) important for utility planning.

o Uncertainties associated with the development and characterization of climate change scenarios for utility areas from global "grid square" data.

o Use of a single source of climate change information, although the use of the GISS transient experiment results for 2010 and 2055 indicates relative sensitivities to small and large temperature changes.

o Uncertainties regarding the concept, methods, and assumptions in developing and applying the estimates of parameters representing the weather-sensitivity of demand.

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[2] To provide some perspective, the generating capacity of a large nuclear or coal-fired baseload powerplant typically ranges from 0.6 to 1.0 GW. Natural gas or oil-fired peaking plants are much smaller.

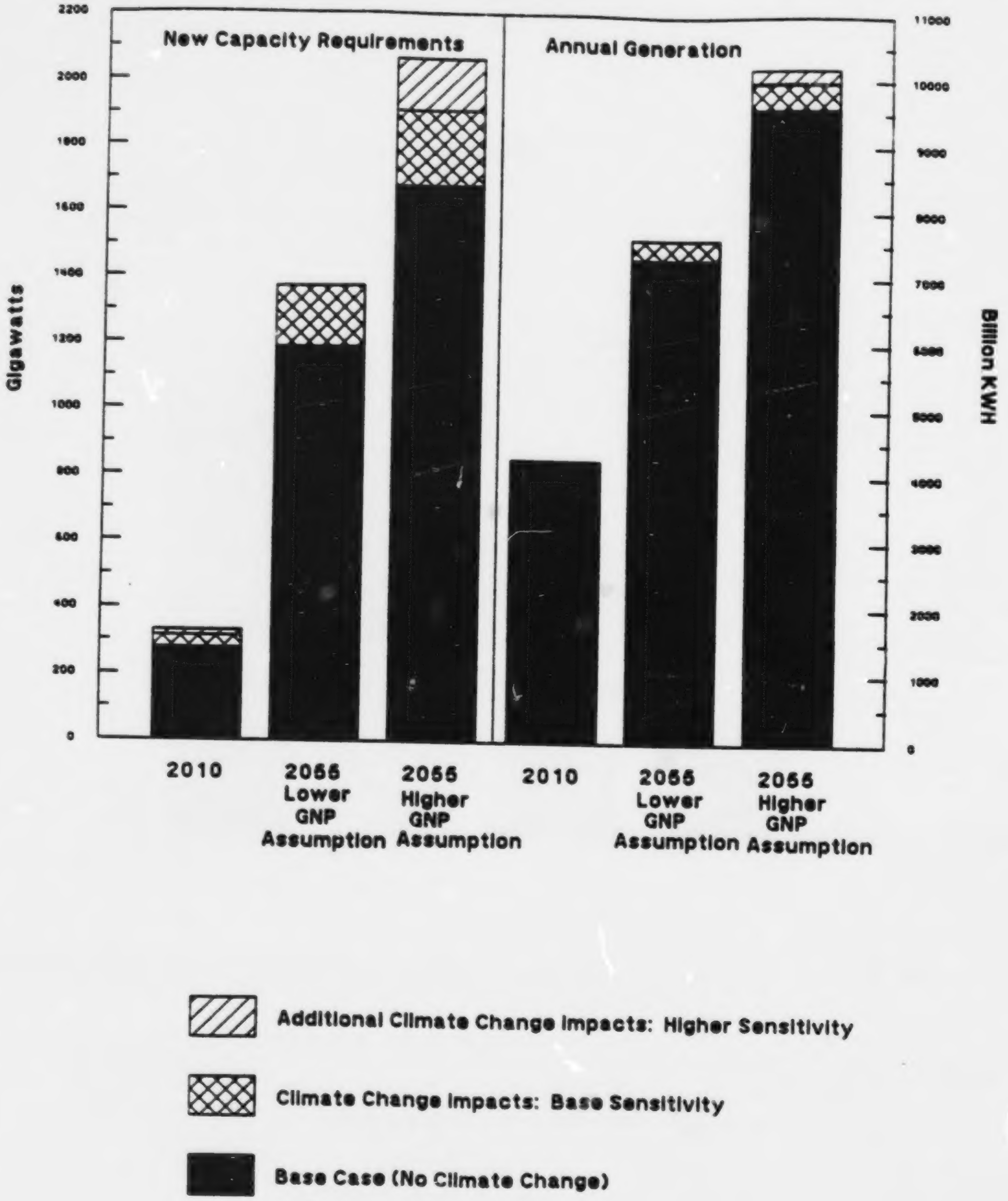

Figure S-1. Potential impacts of climate change on electric utilities in the United States.

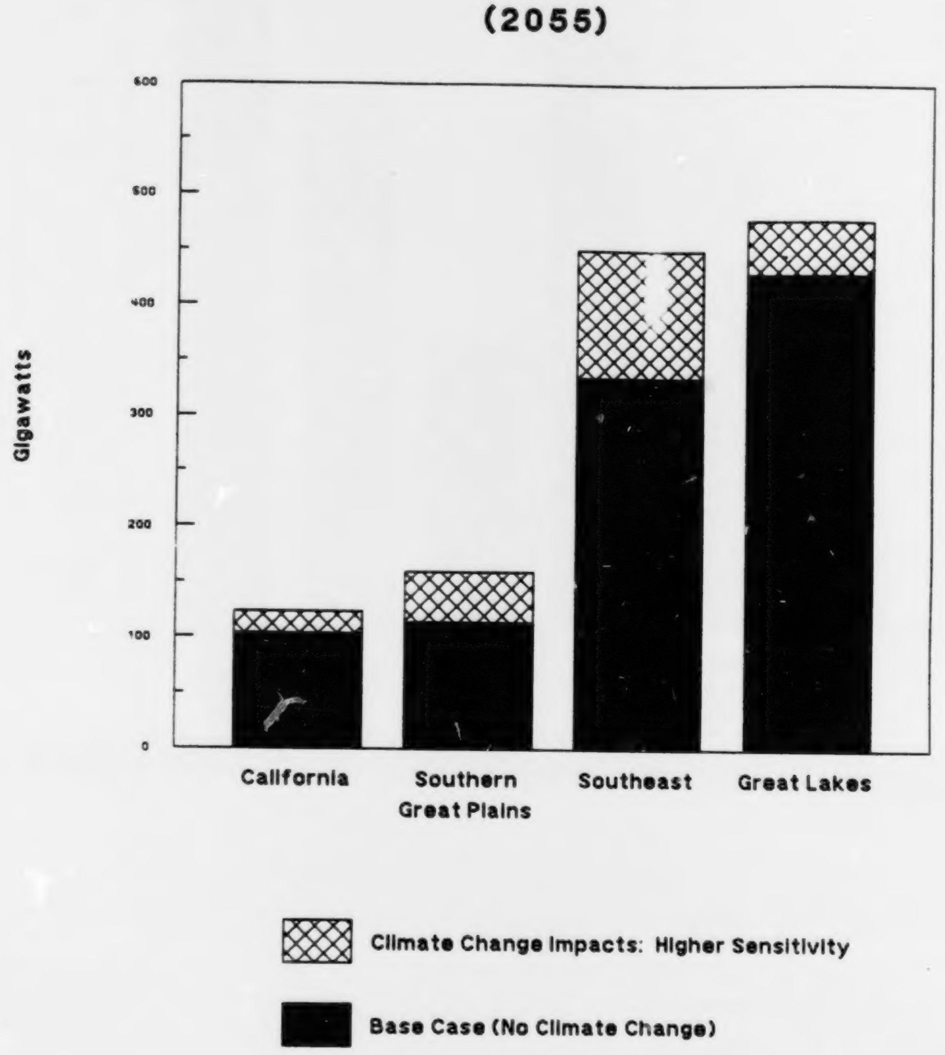

Figure S-2. Potential impacts of climate change on electric generation capacity requirements.

- Uncertainties regarding market, regulatory, technological, and other conditions that will be facing the utility industry in the future independent of climate change.

The analysis was structured to develop reasonable estimates of potential temperature changes on electricity demand, and to assess the implications of these changes in demand for utility planning and operations. Recognizing the points made above, the impact estimates are uncertain and are sensitive to particular assumptions that have been made. However, our findings indicate that utility planners and policy makers should begin now to address more fully and to consider climate change as a factor -- along with other uncertainties and issues -- affecting their planning analyses and decisions. Specific implications of the findings include:

- Estimated regional impacts differ substantially. The largest changes are anticipated in the Southeast and the Southwest, where air conditioning is a particularly important use of electricity.
- The regional analyses suggest that there may be important, new opportunities as a result of climate change for future bulk power exchanges or capacity sales.
- To the extent that the majority of new capacity requirements induced by climate change is for peaking capacity, this implies a new technological and market focus on these types of generating plants.
- A greater focus on short lead-time peaking capacity at the margin affords utilities more planning flexibility to respond to short-term changes in climate or other uncertain conditions.
- Increased electricity demands could increase the difficulty of achieving energy conservation goals that represent one policy option to contribute to atmospheric stabilization.
- Because of the nature and patterns of weather-sensitive demands, climate change could result in different overall fuel mixes for electricity generation than would be expected under base case conditions.
- The impacts of uncertain climate conditions in the long-term potentially poses significant planning and economic risks to the utility industry.

CHAPTER 1

INTRODUCTION

This report examines the potential effects of greenhouse gas-induced climate change on regional and national demands for electricity and the implications of these changes in demands for utility planning and operations. Climate change could affect electric utilities through several pathways. These pathways include the availability of electricity supply resources (e.g., availability of stream flow for hydropower generation; availability of solar, wind, and other renewable generating resources) and conditions influencing facility and system design (e.g., design of power plant cooling systems, siting of power plants and transmission corridors).

Electricity demands, however, are likely to be a critical impact pathway because of the importance of weather-sensitive customer demands in determining (1) the amount of generating capacity a utility must build and maintain and (2) its operating plans (e.g., fuel procurement, generating unit dispatch) to satisfy daily, seasonal, and annual patterns of electric energy consumption. In addition, the industry is very capital-intensive and has a long planning horizon; uncertainty in future demands associated with potential changes in climate may pose substantial economic risks.

ICF Incorporated recently completed a detailed analysis of the potential impacts of temperature change on case study utility systems over the period 1986 to 2015.[3] The case studies were located in Florida and New York. In this report, our analytic approach is extended and our findings from the case studies serve as inputs to develop estimates of climate change impacts for selected geographic regions and for the U.S. as a whole to the year 2055. The geographic regions correspond to areas subject to other analyses contained in the U.S. Environmental Protection Agency (EPA) report to Congress on climate change impacts, namely the Great Lakes, the Southeastern U.S., the Southern Great Plains, and California.[4] It should be emphasized that sufficient resources were not available to study these regions in the same level of detail as the individual utility system case studies. Therefore, the analyses and results reported here should be considered as preliminary.

Two alternate climate change scenarios were used in the development of the impact estimates. These are "transient experiments" developed by the Goddard Institute of Space Sciences (GISS) for use in the EPA report to Congress. They are designated as "GISS A" and "GISS B." In comparison with GISS A, the GISS B experiment assumes lower atmospheric concentrations of greenhouse gases and more volcanic activity in the future. These climate change scenarios were preferred to outputs representing equilibrium conditions (e.g., conditions associated with a doubling of the atmospheric concentration of carbon dioxide) from other general circulation models (GCM's), because the transient scenarios provide estimates of rates of climate change as well as levels of change. For purposes of this analysis, only changes in monthly mean temperatures were used to characterize future climate changes. More specifically, decadal average monthly temperatures were used to estimate changes in electricity demands in the years 2010 and 2055. In turn, these changes in electricity demands were used to estimate changes in utility generating capacity requirements, annual generation and fuel utilization, and electricity production costs for the two future years.

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[3] "The Potential Impacts of Climate Change on Electric Utilities," published by the New York State Energy Research and Development Authority (NYSERDA), Report 88-2, December 1988, and soon to be published by the Electric Power Research Institute (EPRI). Study sponsors in addition to NYSERDA and EPRI were the Edison Electric Institute and the U.S. Environmental Protection Agency.

[4] As will be described in Chapter 2, the utility planning model used in this analysis requires the definition of geographic regions in terms of aggregations of specific state sub-regions. Thus, the boundaries of the Great Lakes, Southeast, Southern Great Plains, and Northern California contained in this report may not be identical to regional definitions in other impact reports.

Sensitivity analyses were conducted to estimate the utility impacts of uncertainties in other future conditions which may interact with climate change to affect utility planning and operations. The sensitivity analyses address uncertainties in future levels of GNP growth (and, therefore, growth in "base case" electricity demand) and in the estimated response rate of customer electricity demands to given temperature changes.

The remainder of this report is organized as follows. Chapter 2 documents the methods used to estimate the temperature-sensitivity of electricity demand and the impacts of these changes on utility plans and operations. The chapter also describes the methods used to apply the GISS transient climate change scenarios and the design of the sensitivity analyses. Chapter 3 reports the results of the analyses. Finally, Chapter 4 discusses the implications of the results.

CHAPTER 2

METHODOLOGY

OVERVIEW OF ANALYTIC APPROACH

The analytic approach is summarized in Figure 1. The initial steps in the analysis are (Step 1) to use the GISS climate change scenarios to develop alternative temperature change scenarios for state and sub-state utility regions and (Step 2) to estimate the sensitivity of electricity demand to temperature changes in these regions. This information is used to evaluate the potential implications of climate change for future electricity demand.

The results of these steps are used with (Step 3) a set of utility planning assumptions as inputs to a model which simulates utility capacity planning and operations. The model is used (Step 4) to evaluate the implications of climate change for generating capacity requirements, generation and fuel utilization, electricity production costs, and other utility planning factors. Climate change impacts are estimated (Step 5) by comparing these planning model outputs with "base case" outputs (i.e., outputs assuming continuation of current climate conditions).

Key assumptions also were varied to evaluate some of the uncertainties which will affect utility planning in the future. In particular, the rate of growth in base case electricity demands was varied -- corresponding to alternative GNP growth rate assumptions -- as was the estimated sensitivity of electricity demand to future temperature changes. The alternative assumptions were input to the utility planning model to estimate the sensitivity of the model outputs to the assumptions.

As noted in Chapter 1, the analytic approach basically is the same as that used in ICF's analysis of potential climate change impacts on individual case study utility systems.[5] In this study, the approach has been extended to address state and sub-state areas as the unit of analysis. These areas represent aggregations of individual utility systems determined by the utility data base and planning model employed. In all, the 48 contiguous states are divided into 47 utility areas. Resources did not permit a detailed, quantitative examinatiion of weather-sensitivity of demand in each of the areas. Rather, a more qualitative approach was used based upon comparisons of historical electricity demands and climatic conditions in the areas, the results of the case study analyses, and weather-sensitivity studies conducted by several utilities.

Because of this limitation, the findings of the analysis should be considered as preliminary, and results for any individual area or region are subject to more detailed analysis and refinement. Our judgment, however, is that overall the analysis provides reasonable estimates of the direction and order of magnitude of possible climate change impacts on the demand for electricity.

The remaining sections of this chapter describe the methods, data, and assumptions used in undertaking each of the steps illustrated in Figure 1.

---

[5] Time and resource limitations for the present study prevented us from addressing the weather-sensitivity of supply -- particularly the effects of climate change on stream flow as a source of hydropower -- as was done in the case study analysis of New York. The earlier study concluded that climate change may have significant impacts on hydropower availability for some utility systems. One other difference is that the present study does not examine the different economic consequences of utilities responding to climate change with short-term coping strategies vs. including the anticipation of climate change in their long-term plans. The implicit assumption here is that utilities are able to anticipate climate change correctly and include these changes in determining their most economic planning strategies.

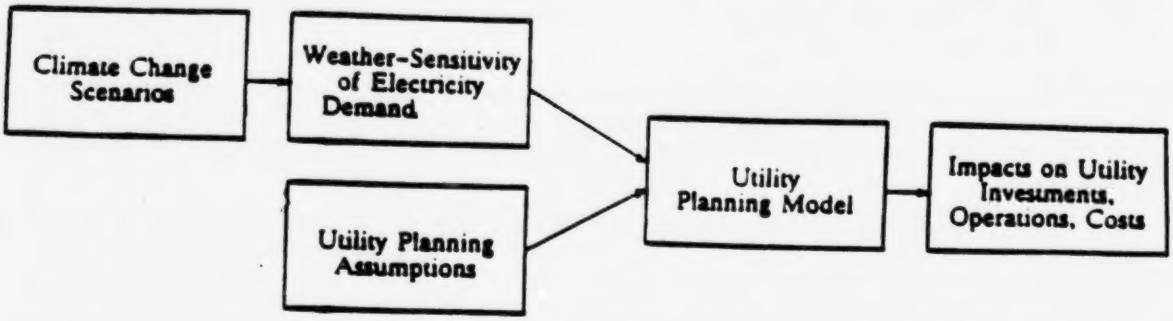

Climate Change Scenarios
Weather-Sensitivity of Electricity Demand
Utility Planning Assumptions
Utility Planning Model
Impacts on Utility Investments, Operations, Costs

Figure 1. Analytic approach.

CLIMATE CHANGE SCENARIOS

The demand for electricity can be affected by many different climate parameters, including temperature, humidity, and wind direction and speed. Seasonal and annual electricity sales are related to climate principally through customer demands for weather-sensitive energy services such as space heating, air conditioning, water heating, and -- for some utilities -- irrigation pumping. The demand for these services as a proportion of total electricity demands varies substantially across regions and utility systems. Weather-sensitive electricity demand can account for up to a quarter or more of a utility's total, annual energy requirements depending upon the mix of electricity sales among various types of customers (residential, commercial, and industrial), customer equipment stocks, electricity prices, and climate.

Further, annual and seasonal peak demands for electricity are highly correlated with the occurrence of extreme temperatures and other conditions associated with events such as summer heat waves and winter storms. The occurrence of these events and customer responses to them are particularly important to utility planners. Because electricity cannot be stored efficiently and must be produced at the same time that it is consumed, the utility must plan to build and maintain enough generating capacity to meet its peak demands with a high degree of reliability.

A trend toward increasing temperatures associated with global warming would tend to increase annual energy requirements and generating capacity requirements for utilities with relatively high air conditioning, irrigation pumping, and other summer seasonal loads. On the other hand, utilities with relatively high space heating and other winter seasonal loads could see their annual energy and generating capacity requirements fall. Some utilities have a fairly even distribution of summer and winter loads, and depending upon the seasonal distribution of temperature changes and customer responses to these changes, the increases and decreases in summer and winter energy requirements could be largely offsetting. For these latter utilities, however, the effects of global warming on seasonal demands and (in particular) extreme events could result in significant impacts on peak demands and generating capacity requirements, even though annual energy requirements would not be affected substantially.

Our challenge in this study was to use available climate model outputs to develop climate change scenarios appropriate from a utility planning and operating context for each of the 47 utility areas. Resource limitations required that the scenario development method be simple and that the calculations be subject to mechanization.

The first decision was to use the outputs of the GISS transient experiments as the source for the climate change scenarios. This decision was made for two principal reasons. First, utilities plan for future years based upon projections of demand growth and other conditions expected to occur in those future years. A utility's obligation to serve requires that it plan for sufficient resources to be available to meet demands of its firm-service customers; on the other hand, there are severe financial and rate penalties associated with building more capacity than needed. The utility planning model used in this study simulates these trade-offs by "optimizing" planning decisions (in an economic sense). However, operation of the utility planning model and estimation of climate change impacts using the model required that utility base cases and climate change-modified cases be developed for specific years. The GISS transient experiments -- as opposed to GCM results characterizing equilibrium conditions (e.g., at $2xCO_2$) at some unspecified future time -- provide this kind of climate change data and are ideal for our purposes.

The second reason is that outputs from earlier GISS transient experiments were used successfully in the individual case study analyses, and thus, these types of experiments have proven to be a useful source of climate change information. Temperature change estimates are reported directly (i.e., measured in degrees rather than as ratios or as estimating relationships) by GISS, and very little additional processing of the data was required to develop inputs for the analysis.

Utility impacts were estimated for two future years -- 2010 and 2055. The first of these years was selected because it is within the current 20-30 year horizon typical of many utility long-term planning analyses. The second year was selected because temperature changes induced by greenhouse gas emissions are expected to follow an increasing trend over time, and a more distant future year would provide estimates of utility impacts under larger temperature changes. The GISS transient experiment results for 2055 approach the magnitude of temperature change impacts that could be expected from a doubling of atmospheric concentrations of CO_2.

In addition, a practical reason for selecting 2055 is that it represents the modeling horizon for one of the GISS transient experiments. GISS B runs to 2029, but GISS A was extended to 2059. Results from the experiments were provided by GISS for analysis as decadal averages of the monthly changes. Therefore, 2055 is the midpoint of the GISS A 2050-2059 decade, and the results of this experiment as provided by GISS could be used directly.

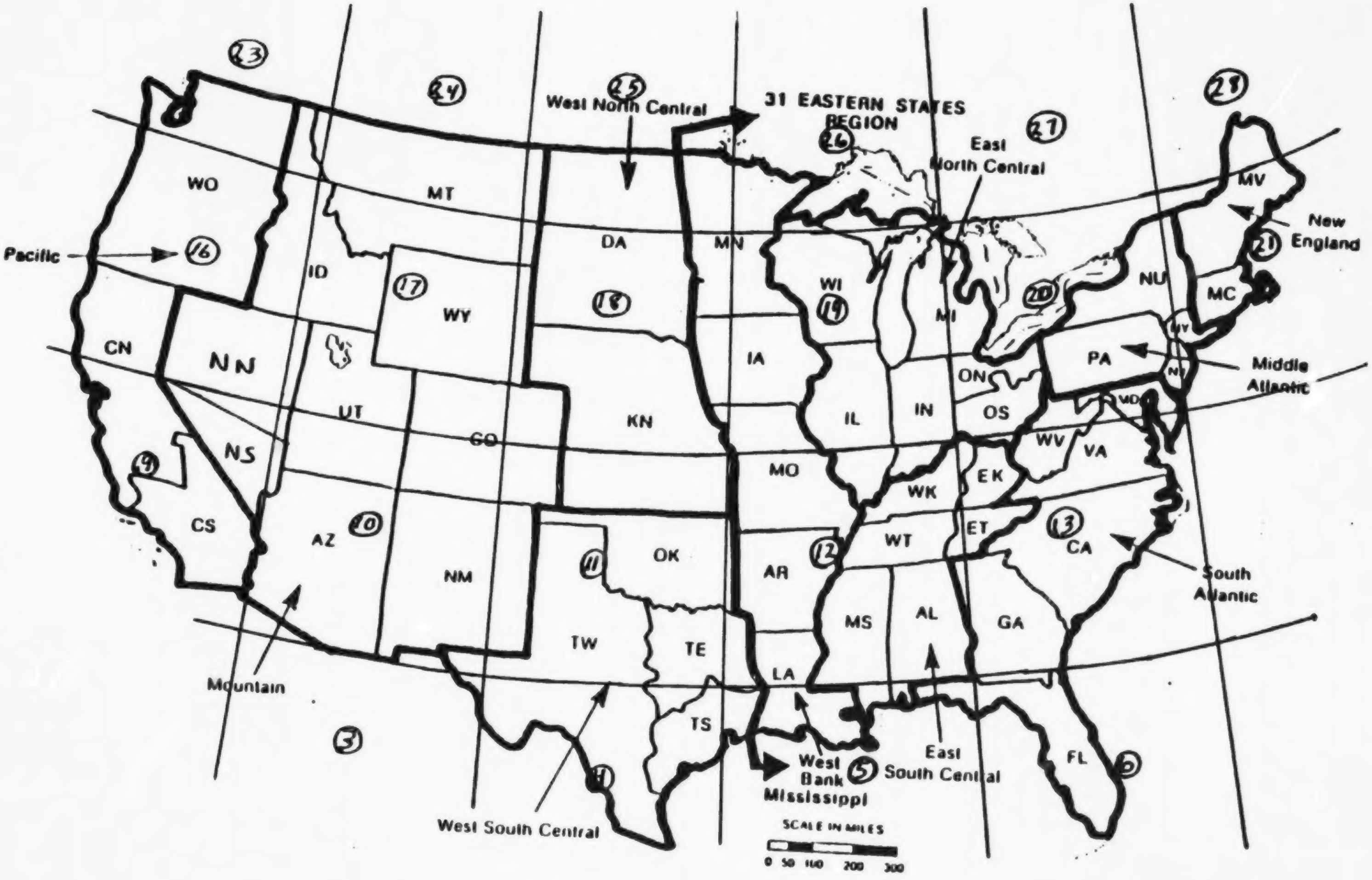
Both GISS A and GISS B results were used in developing alternative temperature change scenarios for the 2010 analyses. Decadal averages of monthly temperature changes for 2000-2009 and 2010-2019 from the Giss A experiment were averaged to provide one set of temperature change data needed to develop utility impacts for 2010. A second set was developed similarly by using decadal averages from the GISS B experiment.

The GISS transient experiment results were provided for geographic regions based upon global "grid squares." Our next task, therefore, was to map the grid square results to the 47 individual utility areas represented in the utility planning model. Figure 2 illustrates the utility areas with an overlay of the GISS grid squares. As can be seen, some utility areas fall unambiguously within a single grid square, and the GISS results for that grid square were used directly. Other utility areas cross boundary lines between grid squares.

For the latter areas, a simple algorithm was used to calculate future temperature change estimates from the grid square data. Maps were consulted which indicated large population centers and, therefore, centers of weather-sensitive electricity demand. If the population centers for a particular utility area were contained largely within one grid square, the area was assigned to that grid square, and the temperature change estimates only for that grid square were used. If the area's population centers were distributed roughly equally between two grid squares, the temperature changes for the two grid squares were averaged. Finally, if a large majority of the population in an area was located in one grid square and a smaller (but substantial) amount in an adjacent grid square, the temperature changes representative of the area were calculated as a weighted average with the grid square weights assigned as two-thirds and one-third, respectively.

The final step in establishing the temperature change scenarios was to determine how the monthly temperature change data would be used to estimate the key impacts on peak demand and energy requirements. Project resources and available utility data and studies on the weather-sensitivity of demand were limited. As a result, detailed weather-sensitivity analyses could not be conducted for each of the utility areas as was done in the system-specific case study analyses. The next section describes how the results of those case study analyses and the limited, available utility studies were used to develop ranges of estimated weather-sensitivity parameters for peak demand and annual energy requirements. The peak demand weather-sensitivity parameter is represented as the percent change in peak demand per degree C temperature change at the time of peak. The annual energy weather-sensitivity parameter is represented as the percent change in annual energy requirements per degree C average annual temperature change.

Therefore, to apply these parameters, estimates of average annual temperature changes and temperature changes at the time of utility area peak demand are needed. The average annual temperature change estimates were calculated from the GISS decadal monthly averages as a simple average of the monthly values. Estimates of temperature changes at the time of utility are a peak demand are more problematic. The discussion above indicated that periods of utility peak demand typically are associated with abnormal or extreme weather conditions. The GISS data do not provide information on the potential effects of global climate change on daily weather patterns and extreme events. Climate change could either exacerbate or smooth the patterns.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West North Central
31 EASTERN STATES REGION
East North Central
New England
Middle Atlantic
South Atlantic
Pacific
Mountain
West South Central
West Bank Mississippi
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TE
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SCALE IN MILES
0 50 100 200 300

Demand region
Alaska (AK) not shown.

Figure 2. CEUM demand regions and GISS grid squares.

In the absence of additional information, our approach for estimating temperature changes at the time of peak demand was to average three summer monthly temperature changes from the GISS data for summer-peaking utilities, and three winter monthly temperature changes for winter-peaking utilities. The three monthly temperatures were averaged to provide a sense of the seasonal temperature changes implied by the GISS transient experiments. We did not select the largest monthly change, because the largest change is not necessarily correlated with the highest temperature values or other non-temperature-related variables that may contribute to a utility's peak.

Table 1 presents our estimates of the average annual change in temperature and the average change in temperature during the season of utility area peak for 2010 and 2055. The average annual temperature changes range from 0.9 to 1.5 degrees C in 2010 for the GISS A transient experiment and from 0.6 to 1.6 degrees C for the GISS B transient experiment. The changes at time of peak are more variable, ranging from 0.6 to 1.8 degrees C in 2010 for GISS A and from -1.0 to 2.1 for GISS B. (Recall that the GISS B experiment assumes lower atmospheric concentrations of greenhouse gases and more volcanic activity.) For 2055, the changes in annual average temperature range from 3.4 to 5.0 degrees C, and the average temperature changes in the seasons of utility peak range from 3.1 to 5.3 degrees C. Based upon our case study analyses where the temperature change scenarios varied from approximately 0.5 to 1.0 degrees C (in 2015), we would expect that the potential impacts on electricity demand of the temperature changes presented in Table 1 would be significant.

WEATHER-SENSITIVITY OF DEMAND

This section describes the development of estimates of the sensitivity of customer demands for electricity to changes in temperatures. In our case study analyses, statistical as well as structural techniques and historical data bases were used to relate changes in demands for electricity to changes in temperature. It was not feasible to duplicate this approach for all of the utility systems in the United States, or even for a subset of "representative" systems. Rather, we relied upon the results of the case study analyses and independent analyses conducted by selected utility systems across the United States to develop a limited set of parameterized weather-sensitivity values. These values differ as a function of utility service area and customer characteristics. Based upon these characteristics, the 47 utility areas were classified according to the expected direction and magnitude of customer responses to temperature changes, and the appropriate weather-sensitivity values were assigned.

Our approach for developing weather-sensitivity values employs several assumptions and simplifications. This implies a wide range of uncertainty surrounding the estimates. Key uncertainties relate to:

- Concept. In our case study work in New York and Florida, equations which related hour-to-hour (or tri-hourly) changes in load to hour-to-hour (or tri-hourly) changes in temperature were developed to produce estimates of the weather-sensitivity of electricity demand. Application of this analytic approach requires interpretation, since the approach assumes that utility customers will respond to changes in the level of average temperatures over the long-term as they do to cope with short-term variations in temperatures. The short-term measures variation in the utilization of weather-sensitive equipment due (principally) to changes in behavior, whereas the long-term must also account for variation in the stock (market saturation and energy-related characteristics) of weather-sensitive equipment.

- Methods. In addition to applying statistical techniques to historical demand and temperature data in the New York case study, we also used a structural model which explicitly accounted for possible increases in the market saturation of weather-sensitive equipment -- air conditioning, in particular. Very different results were obtained using the alternate methods, with the structural approach producing higher estimates of weather-sensitivity. These differences have not been reconciled completely.

TABLE 1

Climate Change Scenarios:
Average Annual Temperature Change and Average Temperature Change in Season of Utility Area Peak
(degrees C)

	2010				2055	
	GISS A		GISS B		GISS A	
Utility Area	Ann.	Peak	Ann.	Peak	Ann.	Peak
Maine/Vermont/NH	1.07	0.85	0.99	1.09	4.43	4.44
Mass./Conn./RI	1.07	1.29	0.99	0.94	4.43	4.10
New York, Upstate	1.12	0.81	0.83	0.22	4.70	4.14
New York, Downstate	1.07	1.29	0.99	0.94	4.43	4.10
Pennsylvania	1.12	0.81	0.83	0.22	4.70	4.14
New Jersey	1.07	1.29	0.99	0.94	4.43	4.10
Maryland/Delaware/DC	1.14	1.08	0.91	0.33	4.54	4.34
Virginia	1.15	1.35	0.99	0.44	4.38	4.53
West Virginia	1.14	1.08	0.91	0.33	4.54	4.34
N. & S. Carolina	1.15	1.35	0.99	0.44	4.38	4.53
Georgia	1.15	1.35	0.99	0.44	4.38	4.53
Florida	0.99	0.92	1.00	0.67	3.43	3.71
Ohio, North	1.12	0.81	0.83	0.22	4.70	4.14
Ohio, South	1.12	0.81	0.83	0.22	4.70	4.14
Michigan	1.05	0.76	0.81	0.19	4.57	3.80
Illinois	1.07	0.90	1.06	0.80	4.55	3.74
Indiana	0.90	0.65	0.78	0.14	4.30	3.12
Wisconsin	0.90	0.65	0.78	0.14	4.30	3.12
Kentucky, East	1.15	1.35	0.99	0.44	4.38	4.53
Kentucky, West	1.41	1.40	1.62	2.12	5.03	4.98
Tennessee, East	1.15	1.35	0.99	0.44	4.38	4.53
Tennessee, West	1.41	1.40	1.62	2.12	5.03	4.98
Alabama	1.41	1.40	1.62	2.12	5.03	4.98
Mississippi	1.41	1.40	1.62	2.12	5.03	4.98
Minnesota	1.12	0.96	0.89	0.42	4.39	3.14
N. & S. Dakota	1.25	1.05	0.86	0.77	4.19	3.44
Iowa	1.04	0.79	0.83	0.33	4.28	3.25
Missouri	1.24	1.15	1.34	1.46	4.79	4.36
Kansas/Nebraska	1.23	1.26	0.98	0.96	4.20	4.09
Arkansas	1.41	1.40	1.62	2.12	5.03	4.98
Oklahoma	1.14	1.45	1.02	1.22	4.18	4.69
Louisiana	1.09	1.41	1.01	1.48	3.78	4.33
Texas, East	1.14	1.45	1.02	1.22	4.18	4.69
Texas, South	1.21	1.85	0.62	0.94	3.93	4.56
Texas, West	1.16	1.59	0.89	1.13	4.10	4.65
Montana	1.35	1.30	1.03	1.38	4.29	4.19
Wyoming	1.48	1.04	1.09	1.24	4.48	3.76
Idaho	1.17	1.08	1.05	0.89	4.12	4.08
Colorado	1.40	1.25	1.08	0.84	4.35	4.19
New Mexico	1.10	0.59	0.66	-1.05	4.63	5.29
Utah	1.36	1.15	0.94	0.30	4.53	5.02
Arizona	1.10	0.59	0.66	-1.05	4.63	5.29
Nevada, North	1.21	0.71	1.07	0.56	4.06	3.48
Nevada, South	1.15	1.27	0.96	1.12	3.54	4.14
Washington/Oregon	1.18	1.11	1.02	1.19	3.92	3.40
California, North	1.17	1.09	0.99	0.89	3.71	3.83
California, South	1.15	1.27	0.96	1.12	3.54	4.14

- Assumptions. Other explicit or implicit assumptions underlying the estimates also are a source of uncertainty. For example, the statistical approach assumes implicitly that the energy-efficiency of weather-sensitive equipment is not changing or is changing at the same rate as in the recent past. Is this a reasonable assumption, or will climate change induce a greater rate of technological change in the future?

The utility studies we relied upon in developing our weather-sensitivity estimates for this analysis all were statistical. While some of the uncertainties described above would tend to be offsetting, our judgment is that the response of electric utility customers to greenhouse gas-induced temperature changes could be greater than the estimates developed from these studies. That is, estimates of changes in electricity demand per degree change in temperature have been used to develop linear weather-sensitivity relationships, but it is quite possible that behavioral responses per degree temperature change will increase as temperatures increase. To address this possibility, we have designed a sensitivity case (described below) which increases the estimated weather-sensitivity parameters by 50%.

Table 2 indicates the utility systems which provided data or in-house studies relating the demand for electricity to changes in temperature and other weather variables. In addition to being geographically dispersed, the utility systems vary across a number of key characteristics such as season of peak demand (summer or winter), mix of customers (by sector), market saturation of weather-sensitive equipment powered by electricity, and annual requirements for weather-related energy services (e.g., heating and cooling). The utilities also differed in terms of characteristics of the data and studies that were available. Differences included:

- Purposes and time periods of the studies,
- Analytic approaches and levels of sophistication,
- Focus on weather impacts on peak demands vs. seasonal or annual sales,
- Definitions of and data sources for weather variables,
- Functional forms and estimation techniques, and
- Levels of disaggregation (e.g., sectoral vs. system).

Despite these differences, the data and studies yielded estimates of temperature-sensitivity that were of a similar order of magnitude, but with variations that could be explained based upon differences in utility characteristics. For example, the estimates from the Florida utility indicated a greater sensitivity of summer peak demand to a given temperature change than was the case for utilities in the North. Further, utilities with high summer loads and service areas concentrated in urban areas showed a strong tendency for annual demands to be positively correlated with temperature changes, while utilities with relatively larger winter loads and rural populations indicated the potential for reductions in annual demands associated with temperature increases. For most of the utilities, winter demands were significantly less sensitive to temperature changes than summer demands, indicating the relatively lower market saturations and utilization of electric heating equipment as compared with air conditioning equipment.[6]

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[6] The exception was the Bonneville Power Administration which markets power to utilities in the Pacific Northwest. This region is characterized by a high market saturation of electric heat and low summer cooling requirements.

Table 2. Sources of Weather-Sensitivity of Demand Data and Studies

Case Study Utilities

- Upstate New York
  - New York Power Authority - Upper New York
  - New York State Electric and Gas
  - Niagara Mohawk Power Company
  - Rochester Electric and Gas
- Downstate New York
  - Central Hudson Gas and Electric
  - Consolidated Edison
  - Long Island Lighting
  - New York Power Authority -- Southeastern New York
  - Orange and Rockland
- A Major Utility in Florida

Other Utilities

- Bonneville Power Administration (Pacific Northwest)
- Boston Edison
- Philadelphia Electric Company
- Southern California Edison
- Tennessee Valley Authority

The studies indicated a range of peak demand sensitivity on the order of 1% to over 6% change in utility system peak demand per degree C. The percent change in annual energy demands for utilities with high summer loads ranged from about 0.5 to 3% per degree C, while comparable values for utilities with high winter loads were a decline of 0.25 to more than 0.50% in annual energy demands per degree C increase in temperature. Based upon these findings, we established parameterized values for "low, medium, and high" temperature-sensitivity for assignment to each of the 47 individual utility areas. The values are as follows:

Peak Demand Sensitivity
(% change in system peak demand per °C)

	Low	Medium	High
Summer-peaking areas	1.35	2.70	5.40
Winter-peaking areas	-1.35	--	--

Annual Demand Sensitivity
(% change in system annual demand per °C)

	Low	Medium	High
High summer load areas	0.45	1.35	2.70
High winter load areas	-0.27	-0.54	--

Note that the range of sensitivities for winter-peaking utility areas and high winter load areas is limited. This is because of the relatively small number of areas which fall into these categories and the similarity of area characteristics. These areas are concentrated in the Northeast, Mountain States, and Northwest.

The next step was to assign a weather-sensitivity value to each utility area. Information was gathered describing a number of factors which would be correlated with the likely direction and order of magnitude of an area's response to changes in temperature. These factors included:

- Average electricity use (in kwh) per residential customer. This is a surrogate for holdings and utilization of weather-sensitive electric appliances and equipment.
- Electricity sales to industrial customers as a percent of total sales. Weather-sensitivity is inversely related to this factor because of the relatively low proportion of electricity use in the industrial sector attributed to space conditioning and other weather-sensitive end-uses.
- Estimated annual load factor. Load factor relates peak demand to total electric generation; a low load factor is associated with a relatively high peak demand and high peak weather-sensitivity.
- Summer-winter peak demand ratio. This ratio indicates the extent to which a utility's peak and seasonal demands tend to be concentrated in a particular season or are distributed more evenly across the seasons.

- Heating degree days and cooling degree days. These temperature data also provide information on the likely seasonal distribution of electricity demands and the relative utilization of weather-sensitive equipment.

Judgmental consideration of each of these factors led to the classification of each utility area in terms of (1) the direction of change in peak demand and annual energy requirements associated with a given change in temperatures and (2) whether the magnitude of change in demand would likely be low, medium, or high. The results of this process are indicated in Table 3. While not precise for any individual area, our assessment is that the process yielded relative results that are reasonable across all areas.

Note that for several areas the direction and/or magnitude of the peak sensitivity value differs from that for annual energy. These cases all are explainable. For example, the entries for Upstate New York indicate a direct relationship between temperature change and peak demand, but an inverse relationship between temperature change and annual energy. For this area (confirmed by our case study analysis), summer peak is more sensitive than winter peak to temperature change, yet the predominance of seasonal heating loads as compared with seasonal cooling loads leads to annual energy falling by a small amount for every degree increase in average annual temperature.

The estimates of changes in peak demand and annual energy demand induced by climate change are calculated by multiplying the peak season and average annual temperature changes for each utility area (from Table 1) by that area's estimated temperature-sensitivity of demand (from Table 3). The results of these calculations -- as percent changes -- are presented in Table 4. As discussed earlier, there are a number of factors (e.g., technological change, changes in behavioral response) which could change the linear relationships implied by our calculations. Based upon our current state of knowledge and understanding, however, these relationships are considered to be reasonable.

Note from Table 4 that in all areas the absolute value of the change in peak demand is greater than the absolute value of the change in annual energy. This result was expected given the nature of seasonal, weather-sensitive energy services. The table indicates increases in peak demand of 10% or more in some areas in 2010, and 25% or more in 2055. Annual energy changes are more modest, ranging up to about 4% in 2010 and 13% in 2055. These are very substantial changes and, as described in the next chapter, lead to significant impacts on utility planning factors.

UTILITY PLANNING MODEL

Given (1) characteristics of current generating capacity and operating costs as well as (2) performance and cost characteristics of future investment options and operating strategies, a principal objective of utility planning is to meet future generation requirements (i.e., the demand for electricity) at minimum cost. Generally, utilities prepare plans to meet this objective assuming future climatic conditions are the same as or similar to those that have occurred in the recent past. That is, utility plans assume continuation of "typical weather conditions," and do not explicitly consider the possibility of climate change.[7] Because our focus is on estimating how climate change may affect key utility planning factors, planning scenarios assuming no change in climate can serve as a basis for comparison with planning scenarios under alternative assumptions of climate change.

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[7] Exceptions are utilities for which hydropower is an important source of generation. These utilities often conduct extensive analyses of the potential effects of changes in rainfall or run off on the availability of hydropower. However, these analyses typically consider variability around the existing means of these weather variables, and not long-term changes in the means.

TABLE 3

Temperature-Sensitivity Values by Utility Area
(% change per degree C)

Utility Area	Peak Demand	Annual Energy
Maine/Vermont/NH	-1.35	-0.27
Mass./Conn./RI	1.35	-0.54
New York, Upstate	1.35	-0.27
New York, Downstate	2.70	0.45
Pennsylvania	1.35	0.45
New Jersey	2.70	0.45
Maryland/Delaware/DC	2.70	1.35
Virginia	5.40	1.35
West Virginia	1.35	0.45
N. & S. Carolina	5.40	1.35
Georgia	5.40	1.35
Florida	5.40	2.70
Ohio, North	1.35	-0.27
Ohio, South	2.70	0.45
Michigan	1.35	-0.27
Illinois	2.70	0.45
Indiana	1.35	0.45
Wisconsin	1.35	-0.54
Kentucky, East	2.70	1.35
Kentucky, West	2.70	1.35
Tennessee, East	2.70	1.35
Tennessee, West	2.70	1.35
Alabama	2.70	1.35
Mississippi	5.40	2.70
Minnesota	1.35	-0.27
N. & S. Dakota	1.35	-0.54
Iowa	2.70	0.45
Missouri	5.40	1.35
Kansas/Nebraska	5.40	1.35
Arkansas	5.40	2.70
Oklahoma	5.40	2.70
Louisiana	5.40	2.70
Texas, East	5.40	2.70
Texas, South	5.40	2.70
Texas, West	5.40	2.70
Montana	-1.35	-0.27
Wyoming	-1.35	-0.27
Idaho	1.35	-0.27
Colorado	1.35	-0.27
New Mexico	2.70	0.45
Utah	1.35	0.45
Arizona	5.40	2.70
Nevada, North	1.35	-0.54
Nevada, South	5.40	2.70
Washington/Oregon	-1.35	-0.54
California, North	1.35	0.45
California, South	2.70	1.35
Weighted Average	3.07	1.00

TABLE 4

Estimated Change In Peak Demand and Annual Energy Requirements Induced by Climate Change (%)

	2010				2055	
	GISS A		GISS B		GISS A	
Utility Area	Ann.	Peak	Ann.	Peak	Ann.	Peak
Maine/Vermont/NH	-0.288	-1.144	-0.267	-1.473	-1.196	-5.996
Mass./Conn./RI	-0.576	1.737	-0.534	1.273	-2.391	5.538
New York, Upstate	-0.302	1.097	-0.224	0.298	-1.270	5.588
New York, Downstate	0.480	3.474	0.445	2.547	1.993	11.076
Pennsylvania	0.504	1.097	0.373	0.298	2.117	5.588
New Jersey	0.480	3.474	0.445	2.547	1.993	11.076
Maryland/Delaware/DC	.534	2.924	1.231	0.893	6.131	11.707
Virginia	1.557	7.310	1.342	2.382	5.911	24.476
West Virginia	0.511	1.462	0.410	0.447	2.044	5.853
N. & S. Carolina	1.557	7.310	1.342	2.382	5.911	24.476
Georgia	1.557	7.310	1.342	2.382	5.911	24.476
Florida	2.685	4.942	2.711	3.619	9.259	20.043
Ohio, North	-0.302	1.097	-0.224	0.298	-1.270	5.588
Ohio, South	0.504	2.193	0.373	0.596	2.117	11.175
Michigan	-0.283	1.025	-0.220	0.263	-1.234	5.131
Illinois	0.482	2.438	0.477	2.165	2.045	10.109
Indiana	0.407	0.883	0.352	0.194	1.937	4.218
Wisconsin	-0.488	0.883	-0.423	0.194	-2.324	4.218
Kentucky, East	1.557	3.655	1.342	1.191	5.911	12.238
Kentucky, West	1.899	3.783	2.181	5.722	6.789	13.455
Tennessee, East	1.557	3.655	1.342	1.191	5.911	12.238
Tennessee, West	1.899	3.783	2.181	5.722	6.789	13.455
Alabama	1.899	3.783	2.181	5.722	6.789	13.455
Mississippi	3.799	7.567	4.362	11.444	13.579	26.910
Minnesota	-0.301	1.296	-0.241	0.573	-1.177	4.233
N. & S. Dakota	-0.675	1.417	-0.464	1.038	-2.264	4.647
Iowa	0.468	2.131	0.374	0.892	1.924	8.765
Missouri	1.673	6.222	1.806	7.888	6.463	23.564
Kansas/Nebraska	1.654	6.789	1.319	5.196	5.674	22.087
Arkansas	3.799	7.567	4.362	11.444	13.579	26.910
Oklahoma	3.074	7.852	2.766	6.590	11.295	25.325
Louisiana	2.940	7.628	2.736	7.986	10.195	23.387
Texas, East	3.074	7.852	2.766	6.590	11.295	25.325
Texas, South	3.259	9.976	1.682	5.091	10.617	24.634
Texas, West	3.136	8.560	2.405	6.091	11.069	25.095
Montana	-0.363	-1.756	-0.279	-1.869	-1.158	-5.650
Wyoming	-0.400	-1.398	-0.293	-1.670	-1.208	-5.082
Idaho	-0.316	1.458	-0.282	1.201	-1.112	5.512
Colorado	-0.377	1.683	-0.272	1.130	-1.174	5.659
New Mexico	0.496	1.604	0.298	-2.838	2.083	14.270
Utah	0.610	1.557	0.425	0.400	2.037	6.782
Arizona	2.977	3.207	1.788	-5.676	12.495	28.540
Nevada, North	-0.651	0.954	-0.576	0.755	-2.190	4.693
Nevada, South	3.095	6.880	2.581	6.025	9.554	22.362
Washington/Oregon	-0.637	-1.492	-0.552	-1.607	-2.117	-4.585
California, North	0.525	1.473	0.447	1.197	1.670	5.168
California, South	1.548	3.440	1.291	3.012	4.777	11.181

The first step in implementing this approach is to characterize the base case (i.e., no climate change) planning scenarios. For 2010, we have used an existing base case developed by ICF for use in acid rain analyses conducted for EPA. This base case was developed using ICF's Coal and Electric Utilities Model (CEUM). The CEUM is a large scale linear programming model which -- among its many capabilities -- can determine a minimum cost investment and operating strategy to meet future electric demands subject to important utility operating and reliability constraints. The 47 utility areas described above are the analytic elements of the model. Generating capacity and electricity generation must be sufficient to satisfy demand in each area; economic transmission of power between areas is permitted up to existing or planned transmission capacities. Outputs of the CEUM include capacity expansion schedules, fuel use by type, and capital and operating costs for each area. For this analysis, the area outputs are aggregated to provide results for the Great Lakes, Southeast, Southern Great Plains, and California regions and for the U.S. as a whole.

The 2010 base case is characterized by:

- Increasing prices for oil and natural gas (used primarily to generate electricity during peak periods) relative to prices for coal (used primarily for baseload generation).
- Moderate growth in electricity demand (about 2.1% per year from 1986 to 2010).
- Assumed life-extension to 60 years for coal and oil/gas steam plants, implying that few existing plants are retired by 2010.
- Shorter assumed lifetimes for nuclear plants (35 years) and no new capacity additions, resulting in a lower market share for nuclear generation than at present.
- No changes in regulation beyond current requirements; e.g., the base case assumes no federal acid rain legislation.[8]

A base case planning scenario also needed to be developed for 2055. Given the substantial uncertainties in demand growth, technological change, energy policies and regulation, and so forth, any view of the characteristics of the electric utility industry in that year or the pattern of investments undertaken by the industry from the present to 2055 is purely speculative. However, for purposes of this analysis, a base case planning scenario was developed using the CEUM and a number of assumptions regarding future utility market conditions. Key assumptions are:

- Two alternative electricity growth rates were assumed, and therefore, two base case scenarios were developed for 2055. The use of two demand growth assumptions recognizes the importance of this variable in determining overall utility capacity requirements. Further, the alternative rates reflect an important sensitivity case, since climate change effects could be substantially different under the two growth assumptions. The average annual growth rates between 2010 and 2055 are assumed to be 1.1%

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[8] This is not a critical assumption for our analysis. Proposed acid rain legislation principally would affect the operating and production cost characteristics of existing generating capacity. Our focus, on the other hand, is on long-term changes in the requirements for new generating capacity induced by changes in customer demands for electricity; i.e., increments to the base case.

and 1.9% in the "lower growth" and "higher growth" scenarios, respectively. These electricity growth rates are consistent with the range of alternative GNP growth rates being used by EPA to develop energy use scenarios in its report to Congress on atmospheric stabilization.[9]

- World oil prices are assumed to grow in real terms at 1.5% per year from 2010. Real natural gas prices also are assumed to grow at 1.5% per year from 2010, and the growth rate in real coal prices is forecasted by the CEUM to range from 0.5 to 2.0% per year.

- For modeling purposes only, we have assumed that there will be no nuclear generating capacity on line in 2055 (i.e., existing capacity will have been retired, and no new nuclear capacity will be built). This is not a critical assumption; in any case nuclear capacity would be assumed to be "baseloaded," or inframarginal, and fossil-fired capacity (coal, oil, or natural gas) would be on the margin and subject to changes in generating capacity requirements induced by climate change. All existing (built by 1985 or earlier) coal, new coal built by 1995, and existing oil/gas steam plants also are assumed to be retired by 2055.

- Two generic types of capacity are assumed to be available to meet incremental demands associated with customer responses to climate change: coal-fired generating units to meet base and intermediate requirements and oil-/gas-fired generating units to meet peaking requirements.[10] Capacity costs per kilowatt are assumed to stay constant in real terms at 2010 levels. The capital costs are approximately $1,300-1,600/kW for coal-fired baseload capacity and $400-500/kW for oil/gas-fired peaking capacity.[11]

- Imports of electricity from Canada and Mexico are maintained at their 2010 levels; however, power from cogeneration, renewables, and other sources is assumed to increase only to the extent that their market shares for these sources in 2055 are the same as the market shares assumed in 2010.

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[9] Recent trends indicate that electricity growth rates are about 90% of GNP growth rates, although the ratio varies year to year. This relationship could change in the future, but is assumed to be stable in our analyses. One factor that could change the relationship is technological change leading to improvements in energy conversion efficiencies. This would tend to lower electricity growth rates relative to GNP growth rates. The electricity growth rates reported in the text are based upon alternate real GNP growth rate assumptions of:

- 2.25% per year from 2010 to 2025 and 2.0% per year from 2026 to 2055, and

- 1.75% per year from 2010 to 2025 and 1.0% per year from 2026 to 2055.

[10] We recognize that new, innovative technologies will characterize power markets in the future. However, our analysis is focused on distinctions between requirements for peaking capacity vs. baseload capacity in a generic sense, and not on choosing among specific technologies. Substantial uncertainties regarding the cost and performance characteristics of technologies are emerging. Distinctions in our analysis would depend only on current assumptions, and would imply more certainty regarding the eventual development and commercialization of new technologies than is warranted.

[11] These costs vary somewhat by region of the country to account for differences in labor costs, environmental regulations, fuel characteristics, and other regional factors. Capital costs include the generating equipment, pollution control equipment, and transmission "hook up" charges.

A critical input to the operation of the CEUM -- and for estimating the potential impacts of climate change on utilities -- is the demand for electricity, or generation requirements. The level and patterns of these requirements are important for determining (1) the amount of capacity and the types of capacity that constitute a utility area's optimal (i.e., least cost) investment plan as well as (2) the dispatch of this capacity to meet hour-to-hour customer demands.[12] A device for summarizing the characteristics of generation requirements over a period of time is a load duration curve (LDC). An LDC is an ordering of hourly generation values from highest (peak) demand to lowest demand over a period of time (month, season, or year). An example of an LDC is presented in Figure 3. LDCs often are used to represent customer demands and generation requirements in planning optimization or simulation models.

In this study, a single LDC is used to represent annual generation requirements for each utility area. The shape (though not the amplitude) of the base case LDCs for 2055 are assumed to be the same as in the 2010 base case. Changes in peak demand and annual energy demand induced by climate change -- from Table 4 --cause the LDCs to change shape in 2010 and 2055. These adjusted LDCs are input to the CEUM, and the resulting output values for capacity, generation, and fuel utilization, costs, and other factors from the CEUM will differ from the base case values. The differences in the values provide the estimates of climate change impacts.

SUMMARY OF KEY UNCERTAINTIES AND LIMITATIONS

As indicated in the above discussion, a number of key uncertainties and limitations affect the impact analysis, and the results of the analysis are dependent upon several important assumptions. As a result, the cases analyzed should be considered as "scenarios" as opposed to "projections" or "forecasts." Principal uncertainties and limitations include:

- A narrow focus on impact pathways. The analysis addresses only the potential effects of temperature change on the demand for electricity and the consequences of these changes in demand. While this is a critical impact pathway, climate change potentially could affect utilities in several other ways.

- Limited availability of climate change information. In particular, electric utility planning and operations depend critically on variation in weather conditions and the occurrence of extreme events. Available climate change scenarios focus only on changes in average values.

- Uncertainties associated with the development and characterization of climate change scenarios for individual utility areas from grid square data. Included here is our focus only on temperature change scenarios.

- Uncertainties regarding the concept, methods, and assumptions in developing and applying the estimates of the temperature-sensitivity of peak demand and annual energy requirements. Of particular importance here are (1) the "parameterization" of findings from our case study analyses and a set of diverse utility weather-normalization studies; (2) "extrapolation" of the results broadly to the 47 individual utility areas; and (3) the assumption that the estimated (linear) relationships between temperature change and electricity demand will continue in the future across the range of postulated temperature changes in the alternative scenarios.

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[12] Generation requirements differ from customer demands (or sales of electricity by the utility) principally by the amount of losses incurred in transmitting and distributing electricity from the generator to the customer.

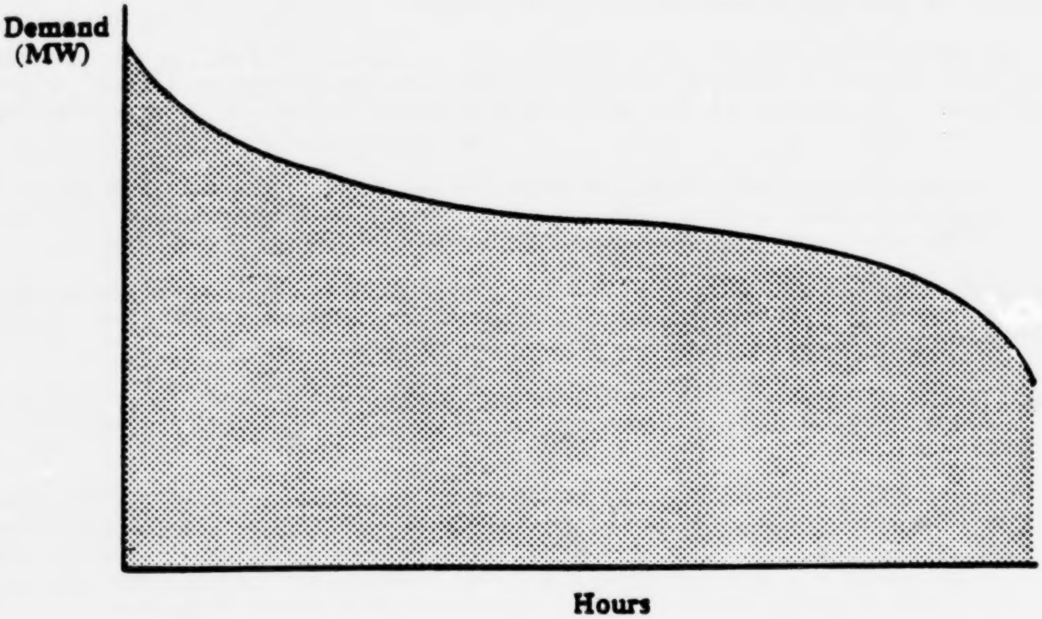


Figure 3. Example load duration curve.

- Uncertainties regarding market, regulatory, technological, and other conditions that will be facing the utility industry in the future independent of climate change, i.e., characterization of the base case utility investment and operating plans.

We have designed a few, select sensitivity cases to address some of these uncertainties and limitations. As described in previous sections, the sensitivity cases include alternative climate change scenarios (GISS A and GISS B in 2010) and alternative GNP/electricity demand growth scenarios. In addition, we have designed a "higher sensitivity" case in which our estimates of the temperature-sensitivity of demand are increased by 50%. Our discussion of temperature-sensitivity suggested that actual sensitivities would be more likely to be higher than lower in comparison with the estimates we developed. Figure 4 summarizes the nine alternative cases reported from the CEUM outputs. Note that the higher temperature-sensitivity estimates are considered only in two cases: in 2010 and in 2055, both assuming GISS A climate change.

Figure 4

SUMMARY OF ALTERNATIVE CASES

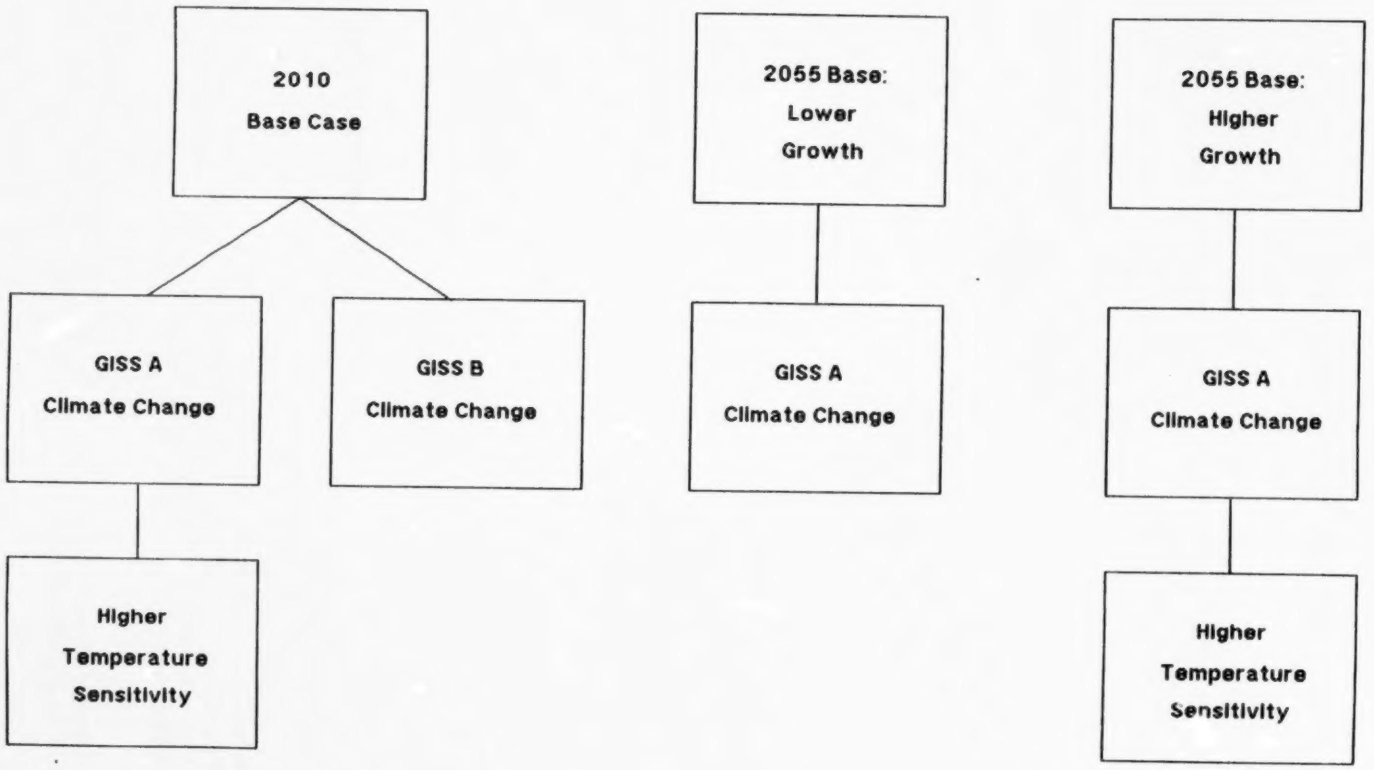
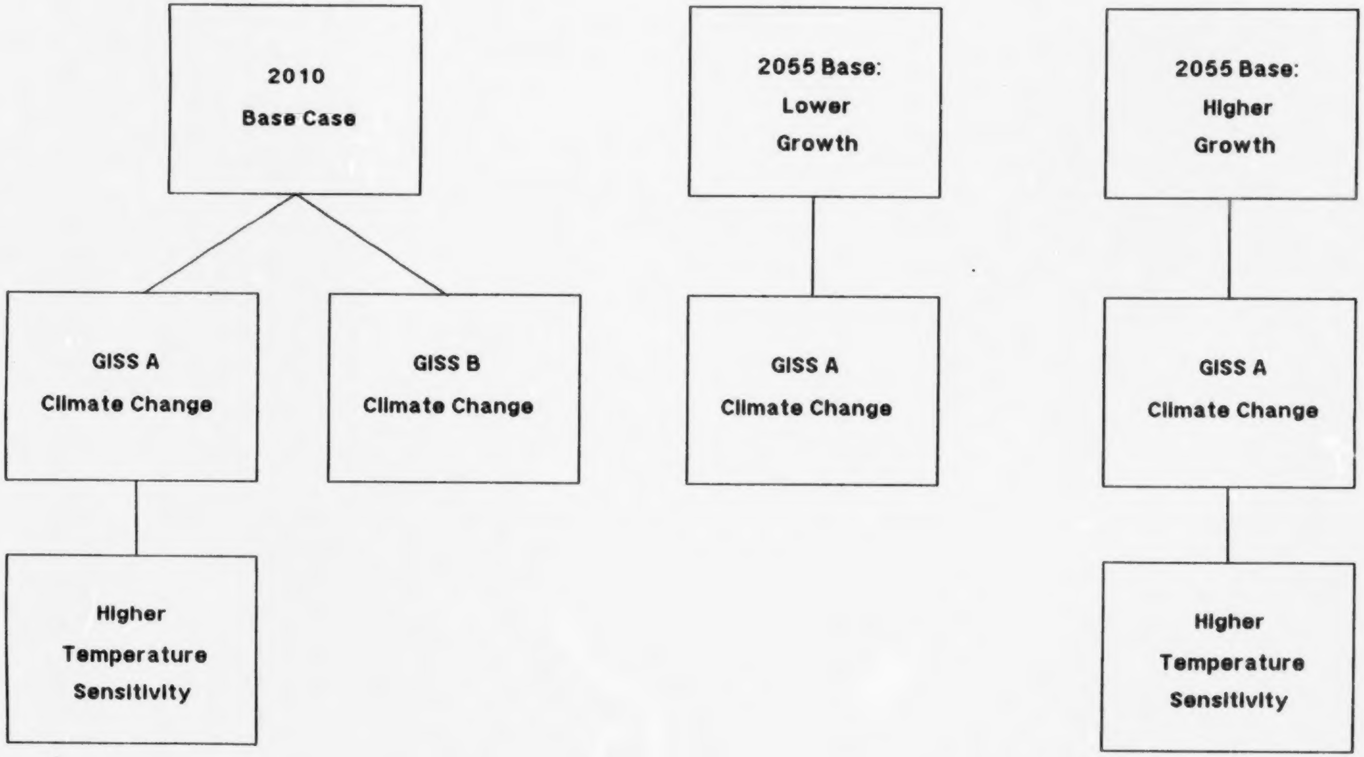

2010
Base Case
GISS A
Climate Change
GISS B
Climate Change
Higher
Temperature
Sensitivity
2055 Base:
Lower
Growth
GISS A
Climate Change
2055 Base:
Higher
Growth
GISS A
Climate Change
Higher
Temperature
Sensitivity

Figure 4

SUMMARY OF ALTERNATIVE CASES


2010
Base Case
GISS A
Climate Change
GISS B
Climate Change
Higher
Temperature
Sensitivity
2055 Base:
Lower
Growth
GISS A
Climate Change
2055 Base:
Higher
Growth
GISS A
Climate Change
Higher
Temperature
Sensitivity

CHAPTER 3

RESULTS

The results of our analyses are sumarized in five tables. One table is presented for each of the following regional aggregations of the CEUM utility areas:

- The Great Lakes (Upstate New York, Pennsylvania, Ohio North, Ohio South, Michigan, Illinois, Indiana, Wisconsin, and Minnesota),
- The Southeast (North and South Carolina, Georgia, Florida, Tennessee East, Tennessee West, Alabama, and Mississippi),
- The Southern Great Plains (Kansas, Nebraska, Oklahoma, Northern (West) Texas),
- California, and
- The United States as a whole.

Each table presents results for the 2010 and 2055 lower growth and higher growth base cases and for the alternative climate change cases. The tables contain esimates of peak demand and annual sales, new capacity requirements (peaking, baseload, and purchased capacity), annual generation (oil/gas-fired, coal-fired, purchased energy, and other), cumulative capital costs, and annual costs for fuel, O&M, capital, and purchases. The entries for the base cases represent totals, while the entries for the climate change cases are increments from the relevant base case. The increments are our estimates of the potential impacts of greenhouse gas-induced temperature change on the demand for electricity and the implications of these demand changes for values of select utility planning factors.

It should be noted that the values presented for new capacity requirements represent only the additional peaking and baseload capacity or capacity purchases from other utility areas that is at the margin: utilities can plan to build or purchase more or less of this capacity to accomodate projected changes in future demands for electricity. Firm scheduled capacity presently in utility plans and assumed levels of hydro, geothermal and other renewables, cogeneration, and other miscellaneous sources of power have been fixed in the model runs and do not vary from case to case. The capital and other costs associated with these sources are included in the base case cost figures. However, these costs do not vary across cases, and therefore, are not included in the incremental costs shown for the climate change cases.

GREAT LAKES REGION

Table 5 presents the results for the Great Lakes region. The table indicates that under base case conditions about 64 GW of new capacity -- as defined above -- would need to be added by 2010 and an additional 300-430 GW between 2010 and 2055, depending upon the assumed growth rate in demand. (To put these numbers in perspective, total generating capacity in the United States currently is on the order of 700 GW.) In the climate change cases, new capacity requirements in the region are estimated to increase by 1.7 to 5.1 GW by 2010, representing an increase of up to 8% as compared with the base case. A large proportion of the increase is in peaking capacity; in fact, baseload capacity requirements are lower in all three of the alternate climate change cases. This result reflects (1) the generally greater sensitivity of peak demand than seasonal or annual energy demands to changes in temperatures and (2) our assumptions that changes in peak are positively correlated with changes in temperature in all utility areas comprising the region, but that changes in annual energy requirements are negatively correlated with changes in temperature in half of these areas. (See Table 3.) Thus, under assumed climate change conditions, the region's economically optimal generation mix includes relatively more peaking capacity and relatively less baseload capacity.

TABLE 5

Summary of Climate Change Impacts: Great Lakes

	2010				2055: Lower Growth		2055: Higher Growth		
		Impacts				Impacts		Impacts	
	BASE	GISS A	GISS B	GISS A Hi Sens	BASE	GISS A	BASE	GISS A	GISS A Hi Sens
Peak Demand (GW)	189.1	2.8	1.3	4.1	331.0	21.9	435.0	28.8	43.4
New Capacity Reqts. (GW)[1]									
· Peaking	17.9	4.9	3.3	6.1	26.4	29.2	43.1	37.9	52.5
· Baseload	46.1	-2.2	-3.1	-1.0	287.2	6.4	394.7	6.6	6.7
· Purchases	--	0.7	1.5	0.0	-9.0	-12.2	-8.5	-12.6	-11.2
· Total	64.0	3.4	1.7	5.1	304.6	23.4	429.3	31.9	48.0
Annual Sales (bkWh)[2]	1009.4	1.1	1.0	1.7	1766.5	8.1	2321.7	10.7	16.1
Annual Generation (bkWh)[2]									
· Oil/Gas	28.4	-1.7	0.7	-1.5	39.5	9.3	54.0	12.2	13.7
· Coal	768.8	-4.8	-7.1	1.9	1,726.7	23.4	2,280.3	25.6	31.9
· Purchases	73.0	6.2	5.0	0.2	14.7	-20.9	25.0	-21.0	-22.7
· Other	214.9	1.5	2.5	1.2	118.1	-3.3	136.5	-5.6	-6.0
· Total	1,085.1	1.2	1.1	1.8	1,899.0	8.5	2,495.8	11.2	16.9
Cumulative Capital Costs[3] (millions of 1986 $)	158,419	309	-1309	2,370	487,934	22,546	714,878	24,868	33,117
Annual Costs (millions of 1986 $)									
· Fuel	15,493	-151	-47	6	41,310	1,886	58,409	3,214	3,826
· O&M	6,544	-4	-50	47	16,931	428	22,510	410	572
· Annualized Capital[3]	15,943	53	-112	261	63,816	2,331	86,469	2,796	3,938
· Purchases[4]	3,285	279	225	9	735	-1,045	1,250	-1,050	-1,135
· Total	41,265	177	16	323	122,792	3,600	168,638	5,370	7,201

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[1] Includes reserve margin requirements; does not include "firm scheduled" capacity. Base case capacity purchases in 2010 set equal to zero.

[2] Includes transmission and distribution losses.

[3] Base case values include regional capital expenditures for utility-related equipment (e.g., transmission facilities) in addition to new generating capacity.

[4] Valued at 45 mills/kwh in 2010 and 50 mills/kwh in 2055.

A somewhat curious result appears in reviewing the annual generation results for 2010. Even though annual energy sales are increasing slightly in the region as a whole in the climate change cases (by about 1.0 to 1.7 bkWh), generation from oil/gas and/or coal-fired powerplants within the region falls in the climate change cases. The reason is that the CEUM allows interregional bulk power sales to take place where economically beneficial and subject to constraints on transmission capacities. The Great Lakes region is a net importer of electricity. In the climate change cases, increasing temperatures in neighboring regions result in additional capacity being built to meet increases in peak and annual energy demands. To the extent that this capacity is not utilized fully in these regions, additional power is available for sale to utilities in states bordering the Great Lakes. Based upon the relative economics of power production in neighboring regions, the CEUM model outputs confirm that net power imports to the Great Lakes region do increase in the climate change cases, resulting in somewhat less reliance on the region's own generating capacity. In the high sensitivity case, however, this effect is very small; capacity is built to meet the more substantial increases in peak demands and annual energy requirements.

Cumulative capital costs to 2010 reflect the changes in new capacity built within the region, and are estimated as $0.3 billion in the GISS A case and $2.4 billion in the GISS A higher sensitivity case. Cumulative capital costs are lower in the GISS B case than in the base case -- by about $1.3 billion -- even though net new capacity additions are slightly positive. The reduction in costs results from the change in capacity mix. Recall that new baseload capacity is assumed to be on the order of $1,300-1,600 per kW, while new peaking capacity costs $400-500 per kW. In this case, the reduction in baseload requirements of 3.1 GW more than offsets the cost of an increase in peaking requirements of 3.3 GW.

The changes in capacity and generation mix for 2010 are reflected in the annual costs for that year. Climate change assumptions result in increases in annual costs of $16-323 million. While these values may seem large, they represent less than 1% of the total annual costs in the 2010 base case. In addition, it is interesting to note the important role of power purchases in determining the overall level and mix of annual costs among cost categories. In the GISS A and GISS B cases, costs for power purchases more than offset reductions in regional fuel, O&M, and capital costs. In the high sensitivity case, more generating requirements are met by resources within the region, and costs for purchases are not much different than in the base case.

By 2055, the impacts are greater as would be expected. New capacity requirements are from 7 to 11% higher in the climate change cases than in the base cases. There is still a predominance of requirements for peaking capacity; in fact, in two of the climate change cases, peaking capacity additions more than double as compared with the base case. Changes in baseload capacity requirements are a more modest 1 to 2%.

The increases in total generation requirements due to climate change are less than 1%. The increases are being met with capacity located within the region. In fact, the change in generation mix in the region by 2055 (i.e., greater reliance on less costly regional coal-fired generation) results in an increase of 2% in generation from regional resources and the displacement of about 20 bkWh of net power imports in that year.

Cumulative capital costs from 2010 to 2055 are estimated to increase by $23-33 billion, and annual costs for 2055 are estimated to increase by $4-7 billion. These represent cost increases of 3-4% compared with the base case costs. While significant, the climate change-induced cost increases are substantially less than the almost 40% differences in costs resulting from the alternative (lower and higher) base case demand growth assumptions. We have not bounded the uncertainty in climate change or demand growth in our analysis; however, the implication is that there are other uncertain conditions that may affect utility planning in the region that are potentially as important or more important than climate change in the long term.

SOUTHEAST REGION

The results for the Southeast region are presented in Table 6. Generally, the base case new capacity requirements and generation are lower than in the Great Lakes region, but the estimated climate change impacts

TABLE 6

Summary of Climate Change Impacts: Southeast

	2010				2055: Lower Growth		2055: Higher Growth		
		Impacts				Impacts		Impacts	
	BASE	GISS A	GISS B	GISS A Hi Sens	BASE	GISS A	BASE	GISS A	GISS A Hi Sens
Peak Demand (GW)	149.9	8.8	5.7	13.2	262.3	54.4	344.7	71.5	107.1
New Capacity Reqts. (GW)[1]									
· Peaking	15.0	6.3	1.4	11.0	3.4	20.4	17.3	45.6	77.8
· Baseload	53.5	4.4	5.4	5.0	232.8	37.7	319.3	27.3	33.5
· Purchases	--	--	0.1	0.1	0.4	-2.2	-1.8	3.9	3.9
· Total	68.5	10.7	6.9	16.1	236.6	55.9	334.8	76.8	115.2
Annual Sales (bkWh)[2]	714.5	14.5	14.4	21.8	1250.3	91.8	1643.3	120.7	181.1
Annual Generation (bkWh)[2]									
· Oil/Gas	50.1	-1.9	-1.6	-3.8	16.0	-12.2	29.9	4.5	17.2
· Coal	588.7	21.4	21.8	23.3	1296.7	131.0	1697.9	125.5	178.2
· Purchases	-50.1	-5.9	-6.9	2.0	-30.2	-19.0	-33.2	1.6	2.3
· Other	190.4	--	--	--	76.8	0.2	92.0	-0.1	-0.9
· Total	779.1	13.6	13.3	21.5	1,359.3	100.0	1,786.6	131.5	196.8
Cumulative Capital Costs[3] (millions of 1986 $)	137,770	9,866	9,064	13,429	349,896	67,646	507,317	68,032	96,687
Annual Costs (millions of 1986 $)									
· Fuel	15,162	526	479	506	33,350	1,303	47,631	4,578	8,324
· O&M	5,539	165	185	201	12,334	1,670	16,319	1,440	1,969
· Annualized Capital[3]	13,688	1,021	902	1,412	47,965	7,798	64,551	8,073	11,552
· Purchases[4]	-2,254	-266	-310	90	-1,510	-950	-1,660	80	115
· Total	32,135	1,446	1,256	2,209	92,139	9,821	126,841	14,171	21,960

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[1] Includes reserve margin requirements; does not include "firm scheduled" capacity. Base case capacity purchases in 2010 set equal to zero.

[2] Includes transmission and distribution losses.

[3] Base case values include regional capital expenditures for utility-related equipment (e.g., transmission facilities) in addition to new generating capacity.

[4] Valued at 45 mills/kwh in 2010 and 50 mills/kwh in 2055.

are substantially greater. The incremental amount of new capacity induced by climate change by 2010 ranges from 10-16 GW, or 15-23% above base case requirements. In addition to overall lower capacity requirements, the GISS B results indicate much lower additions of peaking capacity than in either of the GISS A cases in 2010. This is because the temperature change scenarios show a much lower change in peak demand in the GISS B scenario (5.7 GW) than in the GISS A scenarios (8.8-13.2 GW). The annual temperature change values are more comparable in GISS A and GISS B for the areas in this region, however, and new baseload capacity and annual generation requirements are more comparable across the cases.

Changes in inter-regional bulk power sales affect annual generation in the Southeast as they did in the Great Lakes region, but in the opposite direction. The Southeast is a net exporter of electricity (indicated in Table 6 by a negative number). In the GISS A and GISS B cases using the "base" estimates of temperature-sensitivity of demand, the additional capacity built to meet regional reliability requirements is also used to increase generation for sales outside of the region. In the higher sensitivity case, on the other hand, the economics of bulk power sales to other regions also responding to climate change result in a reduction of net exports by about 2 bkWh. The net effect is that the change in annual generation by sources within the region is very similar across the three climate change cases, about 20 bkWh.

The change in cumulative capital costs to 2010 range from $9.1 to 13.4 billion in the climate change cases. The increases are from 6 to almost 10% of the base case costs. The increase in annual costs are on the order of 4 to 7%. These are very significant changes, implying substantial increases in capital requirements to build new generating plants and additional annual costs of $1.3 to over 2.0 billion.

In 2055, the climate change impacts are much larger. New capacity requirements increase by 23-34%, and annual generation increases by 7.5-11.0%. The impact on cumulative capital costs is an increase of $67 to 97 billion, and annual costs increase by $10-22 billion for 2055.

In the Great Lakes region, we pointed out that the increases in costs induced by climate change were substantially lower than the potential impacts of uncertainties in the base case growth in demand. In the Southeast, however, the potential impacts of climate change are of the same magnitude as the impacts of the assumed demand growth uncertainties. For example, the difference in annual costs between the 2055 lower growth base case and the 2055 higher growth base case is about $35 billion. This can be compared with the estimated annual cost increases induced by climate change of $10-22 billion.

SOUTHERN GREAT PLAINS

The results for the Southern Great Plains are summarized in Table 7. The impacts of climate change in this region are more comparable -- on a percentage basis -- to our findings for the Southeast than for the Great Lakes. For example, new capacity requirements by 2010 increase by 15-28% in the climate change cases as compared with the 2010 base case. We also see a reduction in oil/gas generation, and a fairly substantial increase in baseload coal generation (5-9%). Net imports of power from other regions are relatively small, as are the impacts of climate change on net imports.

Cumulative capital costs induced by climate change increase by $3.7-6.7 billion during the period to 2010, and annual costs increase by 3 to 6%. These represent fairly substantial changes.

In 2055, peak demand increases by 24-36% in the climate change cases, and there are comparable increases in new capacity additions. As in the other regions, new capacity requirements are relatively higher for peaking capacity as compared with baseload capacity. Note that in the two higher growth cases, the region changes from a net importer of purchased capacity to a net exporter of purchases capacity, although the absolute values of total capacity purchases are small. Generation in the region increases by about 10-14% under the climate change scenarios.

TABLE 7

Summary of Climate Change Impacts: Southern Great Plains

	2010				2055: Lower Growth		2055: Higher Growth		
		Impacts				Impacts		Impacts	
	BASE	GISS A	GISS B	GISS A Hi Sens	BASE	GISS A	BASE	GISS A	GISS A Hi Sens
Peak Demand (GW)	49.3	3.9	3.0	5.9	86.3	21.0	113.5	27.5	41.3
New Capacity Reqts. (GW)[1]									
· Peaking	4.6	1.1	0.9	1.7	25.3	18.6	35.1	22.9	35.1
· Baseload	15.3	2.2	1.8	3.3	51.1	4.6	73.1	19.1	18.9
· Purchases	--	0.4	0.3	0.5	5.2	-1.3	5.3	-12.2	-9.3
· Total	19.9	3.7	3.0	5.5	81.6	21.9	113.5	29.8	44.7
Annual Sales (bkWh)	220.0	5.9	4.8	8.9	385.3	37.2	506.5	48.8	73.1
Annual Generation (bkWh)[2]									
· Oil/Gas	29.4	-4.0	-3.4	-5.9	32.9	5.2	43.6	6.9	10.3
· Coal	172.0	10.4	8.5	15.5	325.2	30.7	429.2	103.4	108.6
· Purchases	14.7	0.1	0.1	0.0	34.5	5.1	44.3	-55.8	-37.4
· Other	26.0	0.1	0.2	0.2	31.0	0.0	39.7	-0.7	-0.9
· Total	242.1	6.6	5.4	9.8	423.6	41.0	556.8	53.8	80.6
Cumulative Capital Costs[3] (millions of 1986 $)	39,509	4,536	3,668	6,652	100,539	19,854	151,267	44,725	53,304
Annual Costs (millions of 1986 $)									
· Fuel	4,987	-73	-73	-94	11,841	1,528	16,421	3,866	4,603
· O&M	1,380	88	73	128	3,353	422	4,497	1,147	1,258
· Annualized Capital[3]	3,944	454	369	667	14,400	2,582	19,572	5,043	6,223
· Purchases[4]	662	4	4	0	1,725	255	2,215	-2,790	-1,870
· Total	10,973	473	373	701	31,319	4,787	42,705	7,266	10,214

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[1] Includes reserve margin requirements; does not include "firm scheduled" capacity. Base case capacity purchases in 2010 set equal to zero.

[2] Includes transmission and distribution losses.

[3] Base case values include regional capital expenditures for utility-related equipment (e.g., transmission facilities) in addition to new generating capacity.

[4] Valued at 45 mills/kwh in 2010 and 50 mills/kwh in 2055.

Cumulative capital costs in the region increase by $20-53 billion in the climate change cases, which can be compared with the difference in cumulative capital costs between the lower growth and higher growth base cases of $50 billion. Here, the climate change impacts nearly equal the load growth uncertainty reflected by the alternative base cases. Similarly, the estimated changes in annual costs induced by climate change range from $5-10 billion, nearly the same as the difference in base case estimates of $11 billion.

CALIFORNIA

The estimated temperature-sensitivities of demand and the climate change scenarios for California result in an estimated increase in generating capacity requirements up to 3 GW in the state by 2010 as indicated in Table 8. New baseload coal and peaking capacity additions in the base case are relatively small because of significant amounts of geothermal, cogeneration, renewables, and other dispersed sources of power assumed to come on line during the period. In the higher sensitivity case, annual generation is estimated to increase by about 5.8 bkWh, cumulative capital costs by $4.5 billion, and annual costs by almost $300 million.

By 2055, the estimated impacts are greater. New capacity requirements increase by 13-20%, and annual generation increases by 3-5%. However, baseload (designated here as "coal") generation in the region increases by 12-17% in the high-growth case, displacing significant amounts of power purchases. Siting of baseload coal generating plants in California is problematic at present, and a more constrained analysis likely would result in fewer additions of baseload capacity in the state, and greater continued reliance on generating resources outside the state.

The change in cumulative capital costs ranges from $6.6 billion (7%) in the lower growth case to $23.0 billion (15%) in the higher growth, higher sensitivity case. Annual costs increase by 7-11%, reaching $4.7 billion in the highest impact case for the year. As in the Great Lakes region, these increases tend to be smaller in magnitude than the impacts of the assumed levels of load growth uncertainty in the base cases.

UNITED STATES

Table 9 presents the aggregated results for the United States. In 2010, climate change is estimated to induce increases in new capacity requirements of 9-19% -- up to 54 GW, or more than 1 GW per state on average. As we found with the regional results, the majority of the increase is in peaking capacity to meet the estimated increase in peak demands and maintain utility system service reliability. Increases in peaking capacity range up to 65%, while increases in baseload capacity are less than 10%. Note that as an alternative to building substantial amounts of peaking capacity, utilities may consider options -- such as load management programs or innovative rate designs like time-of-day rates -- to shift customer usage patterns, thereby reducing peak load impacts.

Although total generation increases from 43 to 73 bkWh, the CEUM results indicate an overall reduction in oil-/gas-fired generation in 2010 in the climate change cases. The reason is that the new coal-fired baseload capacity built to meet the additional energy demands induced by climate change is not fully utilized in this pursuit. This makes these plants available to generate additional electricity and displace more expensive oil/gas-fired generation from existing baseload and intermediate plants. This result was one of the principal findings of our earlier case studies, since both New York and Florida are states with substantial amounts of existing oil-/gas-fired generating plants. By 2055, all the uneconomic oil-/gas-fired baseload and intermediate generating plants are retired; climate change leads to positive impacts on oil-/gas generation where necessary to meet peak loads.

TABLE 8

Summary of Climate Change Impacts: California

	2010				2055: Lower Growth		2055: Higher Growth		
		Impacts				Impacts		Impacts	
	BASE	GISS A	GISS B	GISS A Hi Sens	BASE	GISS A	BASE	GISS A	GISS A Hi Sens
Peak Demand (GW)	63.8	1.7	1.4	2.5	111.6	9.6	146.6	12.6	19.0
New Capacity Reqts. (GW)[1]									
· Peaking	0.0	0.0	0.0	0.0	24.6	8.7	29.2	8.3	12.6
· Baseload	6.8	1.7	1.4	2.5	37.9	0.6	63.1	5.5	8.0
· Purchases	--	0.3	1.0	0.5	8.2	0.7	10.4	-0.3	-0.4
· Total	6.8	2.0	2.4	3.0	70.7	10.0	102.7	13.5	20.2
Annual Sales (bkWh)	305.7	3.4	2.8	5.0	535.1	18.3	703.3	24.0	36.1
Annual Generation (bkWh)[2]									
· Oil/Gas	25.9	-5.1	-4.1	-7.5	10.8	1.2	14.7	1.4	2.0
· Coal	39.9	9.8	7.7	14.6	218.9	11.6	332.6	40.0	57.3
· Purchases	99.4	-1.1	-0.7	-1.7	146.0	7.1	160.2	-15.1	-19.0
· Other	180.2	0.2	0.3	0.4	228.7	0.8	286.8	1.0	0.7
· Total	345.4	3.8	3.2	5.8	604.4	20.7	794.3	27.3	41.0
Cumulative Capital Costs[3] (millions of 1986 $)	33,528	2,978	2,382	4,455	94,784	6,630	156,370	15,544	23,006
Annual Costs (millions of 1986 $)									
· Fuel	2,180	-118	-98	-172	7,470	545	11,688	1,588	2,204
· O&M	1,084	73	59	110	2,462	139	3,912	467	676
· Annualized Capital[3]	3,343	291	232	434	12,923	1,029	19,046	1,893	2,809
· Purchases[4]	4,473	-50	-32	-77	7,300	355	8,010	-755	-950
· Total	11,080	196	161	295	30,155	2,068	42,656	3,193	4,739

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[1] Includes reserve margin requirements; does not include "firm scheduled" capacity. Base case capacity purchases in 2010 set equal to zero.

[2] Includes transmission and distribution losses.

[3] Base case values include regional capital expenditures for utility-related equipment (e.g., transmission facilities) in addition to new generating capacity.

[4] Valued at 45 mills/kwh in 2010 and 50 mills/kwh in 2055.

TABLE 9

Summary of Climate Change Impacts: United States

	2010				2055: Lower Growth		2055: Higher Growth		
		Impacts				Impacts		Impacts	
	BASE	GISS A	GISS B	GISS A Hi Sens	BASE	GISS A	BASE	GISS A	GISS A Hi Sens
ak Demand (GW)	774.0	29.4	19.7	44.2	1,354.6	181.1	1,780.3	238.0	356.9
w Capacity Reqts. (GW)[1]									
· Peaking	50.4	21.9	12.9	32.5	175.7	117.8	253.7	182.0	285.8
· Baseload	225.7	14.4	11.4	21.6	1,011.2	67.0	1422.9	73.6	98.2
· Purchases	--	--	--	--	--	--	--	--	--
· Total	276.1	36.3	24.3	54.1	1,186.9	184.8	1,676.6	227.1	384.0
nual Sales (bkWh)	3,846.8	44.5	39.4	66.8	6,731.9	281.4	8,847.8	369.8	554.7
nual Generation (bkWh)[2]									
· Oil/Gas	287.3	-18.4	-12.4	-29.4	221.4	1.7	308.2	26.8	51.2
· Coal	2,797.5	68.0	54.0	102.8	6,241.6	305.3	8,295.4	381.8	559.8
· Purchases	--	--	--	--	--	--	--	--	--
· Other	1,092.0	-1.2	1.2	-0.9	846.4	-1.6	1,003.1	-7.2	0.0
· Total	4,176.8	48.4	42.8	72.5	7,309.4	305.4	9,606.7	401.4	611.0
mulative Capital Costs[3] illions of 1986 $)	668,740	32,302	24,700	48,230	1,765,315	173,362	2,650,037	221,913	328,072
nual Costs illions of 1986 $)									
· Fuel	69,015	188	257	238	172,218	7,788	244,143	16,839	26,488
· O&M	26,085	614	478	918	60,793	3,992	81,853	4,689	6,855
· Annualized Capital[3]	66,578	3,279	2,484	4,900	241,129	21,279	329,015	26,597	39,593
· Purchases[4]	--	--	--	--	--	--	--	--	--
· Total	161,678	4,080	3,219	6,056	474,140	33,059	655,011	48,125	72,936

Includes reserve margin requirements; does not include "firm scheduled" capacity. Base case capacity purchases in 2010 set equal to zero.

Includes transmission and distribution losses.

Base case values include regional capital expenditures for utility-related equipment (e.g., transmission facilities) in addition to new generating capacity.

Valued at 45 mills/kwh in 2010 and 50 mills/kwh in 2055.

Climate change-induced cumulative capital cost increases range up to $48 billion by 2010. This is an increase of about 7% compared with the base case. Annual costs increase by up to $6.0 billion, or 4%. Note that the annual fuel costs in the GISS A and GISS A higher sensitivity cases are lower than in the GISS B case, despite lower total generation in the latter case. This results from the greater displacement of oil/gas use in the GISS A cases, and more reliance on less costly coal as a generating fuel.

By 2055, new capacity requirements induced by climate change increase by 14-23% over base case values, or by 185-384 GW. Recall that total U.S. generating capacity currently is about 700 GW. Clearly, this is a significant potential impact. A mitigating factor is that much of the increase is in short lead-time, lower capital cost peaking capacity. Investment in this type of capacity can be deferred, pending resolution of uncertainties related to potential changes in climate. The cumulative capital costs for total capacity additions ranges from $173 to 328 billion, or up to 12% above the base case values.

Climate change is estimated to induce annual generation increases of about 5-7%, or 305-611 bkWh in 2055. The adequacy of coal reserves to support these levels of generation or, as an alternative, technological change designed to increase the efficiency of energy resource conversion and utilization are issues requiring further analysis.

The annual costs in 2055 for fuel, O&M expenses, and capital are estimated to increase by $33-73 billion. These figures represent increases from base case values of 7-11%.

CHAPTER 4

IMPLICATIONS OF RESULTS

The results presented in the previous chapter indicate that temperature change potentially can have significant impacts on peak demands, annual electricity sales, electric generating capacity requirements, annual generation and fuel utilization, and costs. Based upon the climate change scenarios, estimated temperature-sensitivities of demand, and other assumptions, significant impacts -- involving billions of dollars for the United States as a whole -- may occur by 2010, well within utility long-term planning horizons of 20-30 years. The potential impacts are substantially greater by 2055.

The results indicate that climate change impacts are uncertain -- they could be higher or lower than we have estimated -- and that their estimated orders of magnitude are sensitive to a number of assumptions made in the analysis. Thus, additional research must be conducted to refine the data and methods to test the robustness of the findings and to expand the analysis to include other impact pathways. However, as concluded in our case study report, the results imply that utility planners and policy makers should begin now to assess more fully and to consider climate change as a factor -- along with other uncertainties and issues -- affecting their planning analyses and decisions.

More specific implications of the results include the following:

- Climate change can affect utilities with different characteristics differently. Impact analyses based upon climate change scenarios covering broad geographic areas (e.g., grid squares) are not likely to capture the unique types of responses from individual utilities or utility areas. Additional research should include data and methods for developing climate change scenarios at the local level.

- A related point is that there clearly are regional differences in the direction and magnitude of the impacts. The differences relate importantly to the utilities' customer mix, weather-sensitive equipment holdings and utilization, general climatic conditions, and other utility area characteristics as well as to the estimated responses to the climate change scenarios. For example, the results point to substantial differences in estimated impacts between the Great Lakes and Southeast regions.

- The regional differences suggest that there may be important, new opportunities as a result of climate change for bulk power exchanges or capacity sales. The results indicate changes in net imports or net exports of power for individual regions across the various climate change cases. In addition, the mix of additional new peaking and baseload capacity requirements in response to climate change differs by region. Diversity in season or time of peak across regions may permit firm capacity sales or sales of emergency power to meet these peaks more efficiently (i.e., investment in fewer plants nationally). To these ends, utilities and regulators would need to give more attention on planning and construction of transmission facilities to alleviate possible constraints on power exchanges.

- To the extent our result is confirmed that the majority of new capacity requirements in response to temperature change is for peaking capacity, this implies a new technological and market focus on these types of generating plants. Current technology R&D and market interest are concentrated more on plants operating in baseload. Related to this would be increased R&D on electricity storage technologies, which would allow electricity to be generated at off-peak times by lower cost, more efficient generating plants for use during peak periods.

- Peaking capacity typically is less capital-intensive and has shorter lead times than baseload capacity. A greater focus on peaking capacity at the margin affords utilities more planning flexibility to respond to short-term changes in climate or other uncertain conditions.

- Because increases in customer demands for electricity may be particularly concentrated in certain seasons and at peak periods, conservation and (especially) load management programs that improve the efficiency or change the patterns of customer uses of electricity could be more cost-effective when considered in light of potential changes in climate. On the other hand, increased electricity demands could increase the difficulty of achieving energy conservation goals that represent one policy option contributing to atmospheric stabilization.

- Because of the nature and patterns of weather-sensitive demands, climate change could result in different overall fuel mixes than would be expected under base case conditions. This was seen, for example, in the results for the Southeastern and southern Great Plains regions and for the United States as a whole in 2010. Fuel needs to support fossil-fired generation (assumed to be on the margin) increased substantially in most of the climate change cases in 2055. The implications are that climate change could affect utility fuel planning as well as long-term energy resource policies and planning more generally.

- The impacts of uncertain climate conditions in the long term potentially can pose significant planning and economic risks to the utility industry. The magnitude of the risks estimated here for some regions (e.g., the Southeast and the southern Great Plains) are similar to other uncertainties utility planners and decision-makers must face.

IMPACT OF GLOBAL CLIMATE CHANGE ON URBAN INFRASTRUCTURE

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CHAPTER 1[1]

INTRODUCTION AND GENERAL CONCLUSIONS

This report examines the likely impacts on urban infrastructure of global climate change due to an effective doubling in atmospheric carbon dioxide. It provides case studies of probable impacts on three cities: Cleveland in the Midwest, Miami in the Southeast, and New York City in the Northeast. A fourth case, examining San Diego in the West, was planned, but subsequently was replaced by a cross-cutting impact analysis, which is included in the main text of the EPA Report to Congress.

The study sites were selected jointly by EPA and The Urban Institute based on three criteria:

- A preference for cities/regions where EPA was focusing other effects studies,
- A desire for geographic spread, and
- The existence of Institute contacts and knowledge about area infrastructure conditions that would facilitate study performance in the 3-month period required by EPA's overall study schedule.

A comprehensive examination of infrastructure impacts in three cities would not have been feasible given the study budget and time frame. Recognizing that information about some sites already was being gathered by other EPA contractors and that some impacts would be generic, specific infrastructure elements were picked as primary emphases at each site.

In Cleveland, the Institute already had an inventory of infrastructure conditions and capital needs, which made a comprehensive impact examination feasible. In Miami, the impacts on water distribution, solid waste disposal, sewage treatment, and bridges were targeted for investigation. Three other EPA studies were examining other infrastructure issues in Dade County: Weggel et al. (1989), levees and dikes; Leatherman (1989), beach nourishment and other responses to sea level rise in Miami Beach; and Diamond (1988), water supply. Because the impacts of sea level rise on different infrastructure elements proved to be intertwined, the Miami case subsequently was expanded to cover impacts on streets, drainage, water supply, and oceangates (the structures and strategies used to defend against a rising sea). The infrastructure in New York City is so vast that the case study was largely confined to a single issue, the effects on water supply and demand. Weggel et al. (1989) estimates the impact of sea level rise on the city's oceangates.

Findings by city are presented at the beginning of the individual chapters. Some of the general conclusions that can be drawn from a look at climate effects across the three cities are:

- Climate change will create clear regional winners and losers. Miami and New York stand to incur substantial capital costs; Cleveland, overall, will benefit from milder weather.
- The largest expenses are likely to address water supply and oceangate needs.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under contract no. CR-814883-10-0, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

- Some infrastructure areas do not warrant particular policy attention now. For example, Cleveland air-conditioning costs will rise, but the effect will be gradual, and incremental design adjustments will be an appropriate response.

- Institutional changes likely will result. Because of the need for regional water project financing and resource management, both New York City and Miami will experience greater pressures for intergovernmental cooperation.

- Some immediate policy responses are warranted, particularly in the area of infrastructure planning. Supply and demand projections for New York's water supply, for example, should incorporate climate effects given the long lead times in water project development.

The infrastructure cost implications of global climate change will be much larger if local infrastructure systems experts fail to respond to incremental changes or if change comes through abrupt sawtooth shifts. Tremendous cost savings can be achieved by responding to changes in temperature and sea level at appropriate points in the infrastructure replacement cycle. To assure timely response, the federal government needs to educate infrastructure engineers, planners, and managers about current and projected climate changes and about probable sea level rise. These individuals, in turn, will have to educate State and local elected officials.

The National Flood Insurance Program (NFIP) and national organizations that develop infrastructure standards and model building codes also must anticipate or respond to changes that occur. NFIP floodplain-floodway maps and related local requirements for coastal communities must anticipate sea level rise by 50 to 60 years to avoid huge, yet preventable future insurance losses in the NFIP program. Standards for coastal bridges need to be adjusted slightly in recognition that water levels will rise between reconstruction cycles. And pavement construction standards by climate bands, which require thicker and more costly roadway surfaces in colder climes, must be updated periodically to achieve the savings in paving costs made possible by rising winter temperatures.

ANALOG CITIES WERE USED IN SOME ANALYSES

Some parts of the analysis are based on infrastructure cost experience in cities with current climates similar to the anticipated future climates in New York City and Cleveland. The analog cities were identified in Kalkstein (Volume G), based on a correlation analysis of present temperatures in 48 cities with projected temperatures in the cities of interest after a 7°F temperature rise. The summer analog for New York City is Louisville, Kentucky, which coincidentally is also the summer analog for Cleveland. Cleveland's winter analog is Nashville, Tennessee, while New York's is Portland, Oregon. Each case study includes estimated changes in heating and cooling degree days. These were computed as variations in average daily temperatures above and below 65°F, a definition that is consistent with National Weather Service data. The underlying temperature projections and other weather projections were derived by applying GISS and GFDL estimates of the percentage impacts of an effective doubling in atmospheric carbon dioxide (Jenne, 1988) to historical weather data.

CHAPTER 2

IMPACTS IN MIAMI

SUMMARY

The rise in sea level anticipated in the next century will severely aggravate ponding and flooding problems in Greater Miami due to the rise in the water table, encroachment of seawater, and the effects of storms. Preventing inundation and mitigating the impacts on infrastructure could cost more than $600 million, as detailed in Table 1.

TABLE 1

PROBABLE INFRASTRUCTURE NEEDS AND INVESTMENT IN MIAMI IN RESPONSE TO A DOUBLING OF ATMOSPHERIC CARBON DIOXIDE
(millions of 1987 dollars)

Raising Canals/Levees	$60
Canal Control Structures	$50
Pumping	not estimated
Raising Streets	$250 added to reconstruction cost
Raising Yards	not estimated
Pumped Sewer Connections	estimated
Raising Lots at Reconstruction	not estimated
Drainage	$200-300
Airport	$30
Raising Bridges	not estimated; retrofitting much more costly than raising bridges during reconstruction
Sewer Pipe Corrosion	minimal
Water Supply	not estimated

The impacts of rising temperatures in Miami should be minimal compared to the effects of sea level rise. With an effective doubling in carbon dioxide levels, both the GISS and GFDL models predict an average temperature rise from 75 to 80°F. Precipitation is assumed to remain relatively constant, although modest changes are likely. The GISS model projects a 4-inch annual rise in rainfall, while the GFDL model projects a 2-inch drop.

Table 2 indicates the projected impacts on various types of infrastructure in Greater Miami. Cost-effective adaptation to global climate change will require complex, careful decisions about how and when to adapt the infrastructure. A strong emphasis on life cycle costing and the courage to undertake expensive upgrading in anticipation of future changes will be essential. This will require leadership. It will also require careful examination of the available options for controlling the sea. Hard political decisions will be required about how well Dade County can afford to protect its coastal exposures and how the costs will be split among affected property owners, local governments, the Metropolitan Dade County government, the State of Florida, and the federal government.

Table 2

Potential Impacts of the Greenhouse Effect on the Infrastructure of Greater Miami, Florida
(3.3-Foot Sea Level Rise; 5.5°F in Temperature Rise)

Type of Infrastructure	Impact of Climate Change	Public Sector Responses	Regulatory Design Requirements	Effect on Capital Costs	Effect on Operating Costs
Canals, levees, control structures	Loss in freshwater head and change in hydraulic gradient. More flooding and ponding in wet season magnified by hurricanes. Potential destruction of Everglades and Dade County agriculture. Increased likelihood of intractable water management conflicts.	Build more and raise existing levees based on hydrologic studies. Reconstruct control structures. Add substantial pumping capacity. Dredge canals more frequently.	Adjust control structure stages to fit water management objectives.	$108 million.	Much more pumping.
Streets and Highways	Gradual structural weakening and eventual pavement failure of streets at elevations less than 6 feet due to saturation of base.	Gradually raise elevation of 34% of Miami's streets and highways, driveways, access roads, and buildings 3 feet. Install improved drainage to prevent flooding.	Incrementally revise design features of streets and highways.	$237 million to reconstruct 34% of Miami streets with minimal allowance for improved transitions and drainage.	Significant reconstruction traffic delays and disruption. Uneven streets to affect motor vehicle operating costs.
Bridges and Causeways	Risk of structural weakening and failure of portions of causeways. Washouts more likely with hurricanes. Vertical underclearances of bridges reduced, thus increasing flood backwaters and obstructing a few boats. Potential lifting of culverts. Increased humidity likely to reduce life-cycle of painting systems. Erosion beneath bridge abutments likely to cause differential settlement, stresses, and strains.	Gradually raise some parts of causeways as they reach end of service lives. When bridges due for replacement, raise raise structure height. Raise fenders. Install redesigned culverts over time. Pursue mitigation measures to prevent erosion beneath bridge abutments.	Revise bridge design features and criteria such as design storms.	Large, but much less costly at reconstruction than through retrofit.	Small, but could adversely affect bridge inspection and maintenance of low-elevation structures on nonnavigable waters.
Water Supply	Wells near coast might become brackish. Increased droughts unless hurricanes increase. Increased water demand.	Increase water conservation. Move selected wells inland. Possibly desalinate water.	Revise water management objectives.	Not estimated.	Cost of desalinated water will be three times cost of water from aquifer.

Table 2 continued.

Potential Impacts of the Greenhouse Effect on the Infrastructure of Greater Miami, Florida
(3.3-Foot Sea Level Rise; 5.5 °F Temperature Rise)

Type of Infrastructure	Impact of Climate Changes	Public Sector Responses	Regulatory Design Requirements	Effect on Capital Cost	Effect on Operating Cost
Building and Structure Foundations	Negligible overall effect since footings, seatings, and pilings overdesigned by a factor of 1.5 to 2.0.	Confirm structural stability of foundations through detailed engineering analysis.	Potential revisions in building regulations. Gradually raise Dade County flood criteria and reassess flood insurance maps.	Negligible.	None.
Airports	Risk of prolonged disruption of airport operations after storms due to flooding. Loss of drainage capacity.	Rebuild drainage system for stormwater runoff and add considerable pumping capacity.	Possibly revise design details for airfield pavement reconstruction. Develop new drainage design criteria.	$30 million.	Small operating costs for pumping. Temporary disruption during reconstruction.
Solid Waste	Negligible.	Select sites carefully.	Raise flood criteria.	Negligible.	Negligible.
Sanitary Waste	Severe hurricanes combined with sea level rise could wash considerable Virginia Key fill and sludge into Biscayne Bay. More freshwater and saltwater sewer pipe infiltration. Higher air temperatures could cause sewer pipe failures due to hydrogen sulfide corrosion. Higher temperatures increase rate of bacteriological action and removal of pathogens.	Continue to fight infiltration and hydrogen sulfide corrosion. For raised buildings, adjust pipe connectors and improve pumping. Raise manhole covers.	Modify regulations affecting sewer pipes. Raise flood criteria.	Large. Significant private cost to realign sewer pipes from buildings rebuilt at higher elevations.	Small.
Storm Sewers	Lose reduced ponding and flood control benefits of $267 million, 12-year storm drainage capital improvement program.	Make substantial storm drainage improvements.	Modify regulations and design criteria affecting storm.	$200-300 million.	Moderate pumping costs.

INTRODUCTION

The Miami area exists within an unusually complex environmental setting. An intricate water management system already has evolved to protect the area against flooding, to provide fresh water, to irrigate nearby agricultural lands, and to limit saltwater intrusion, which could harm the Everglades National Park and contaminate much of the potable water supply. The likely impacts of an effective doubling in carbon dioxide on the infrastructure are shaped by the hydrology and existing water management system.

This case study discusses the impacts of global climate change on a wide range of infrastructure -- water supply, canals, levees, water control structures, building and structure foundations, highways, bridges, airports, solid waste disposal facilities, sanitary waste facilities, and storm drainage. Nevertheless, it does not cover all infrastructure impacts. Notable exclusions are the impacts on beach erosion and nourishment and on air-conditioning costs.

FEW DEVELOPED MAINLAND AREAS WILL BE INUNDATED IF SEA LEVEL RISES 3 TO 5 FEET

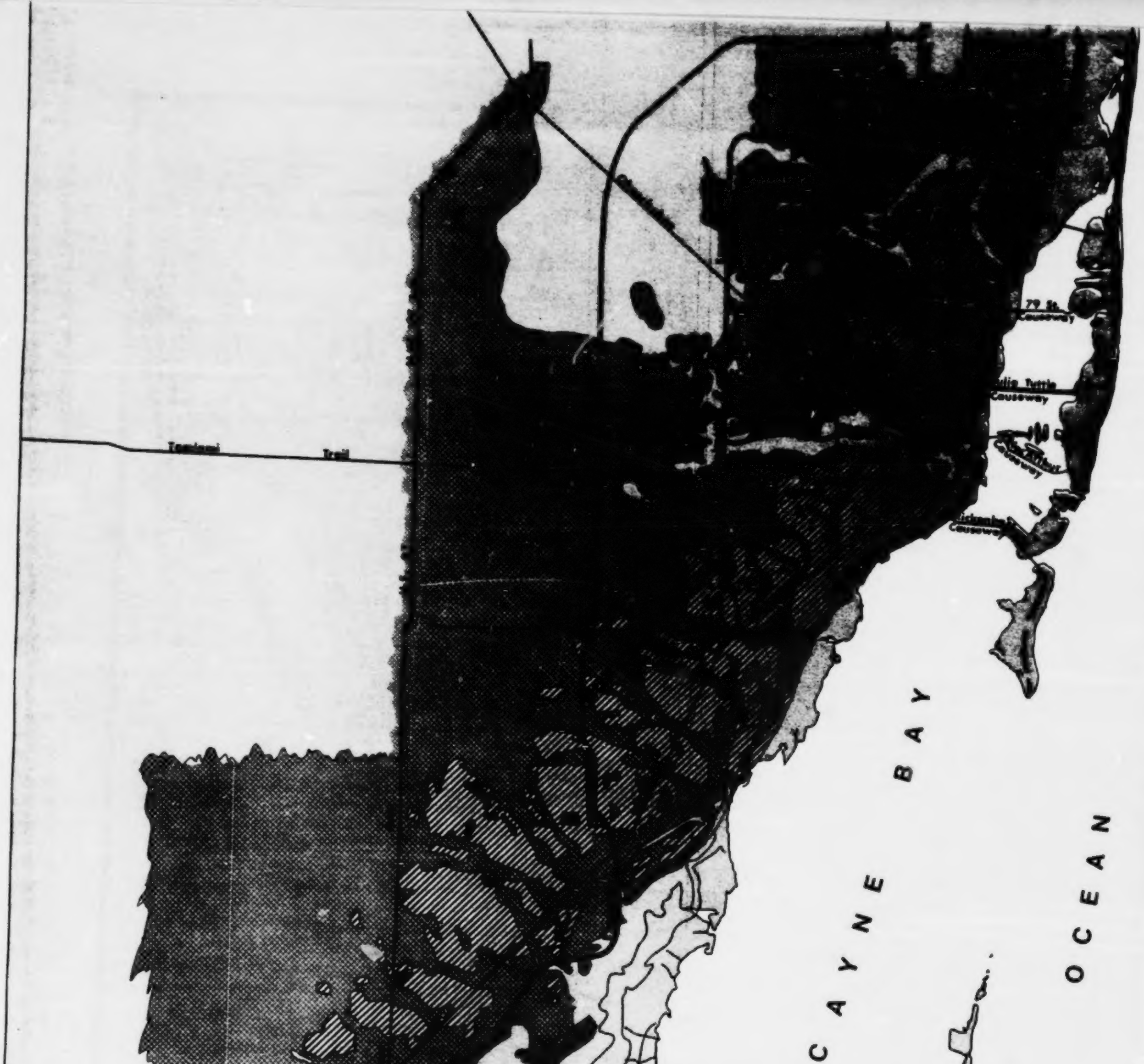
Importantly, Figure 1 shows a 3- to 5-foot rise in sea level will not inundate much of the developed portion of the Miami mainland, although it will increase flooding risk considerably, especially during hurricanes. One area at risk of inundation is the large, low-lying area south of Miami, which is a low-density residential area built on land reclaimed by adding fill. Levees and water control structures used for flood protection in these areas should prevent inundation if they are upgraded. Structures build in these areas generally sit on piles and fill raised 3 to 5 feet above the land surface to reduce flood risks.

DADE COUNTY IS RECLAIMED FROM WATER

Miami is a hydrologic masterwork, a densely populated area bounded by water from below and on all sides. When the city was first developed, the entire southern tip of Florida was a mangrove swamp called the Everglades or River of Grass. The Everglades often was awash in fresh water. The initial settlement was built on local high points of the Atlantic Coastal Ridge, 10 to 23 feet above sea level, and immediately adjacent to Biscayne Bay and the Atlantic Ocean.

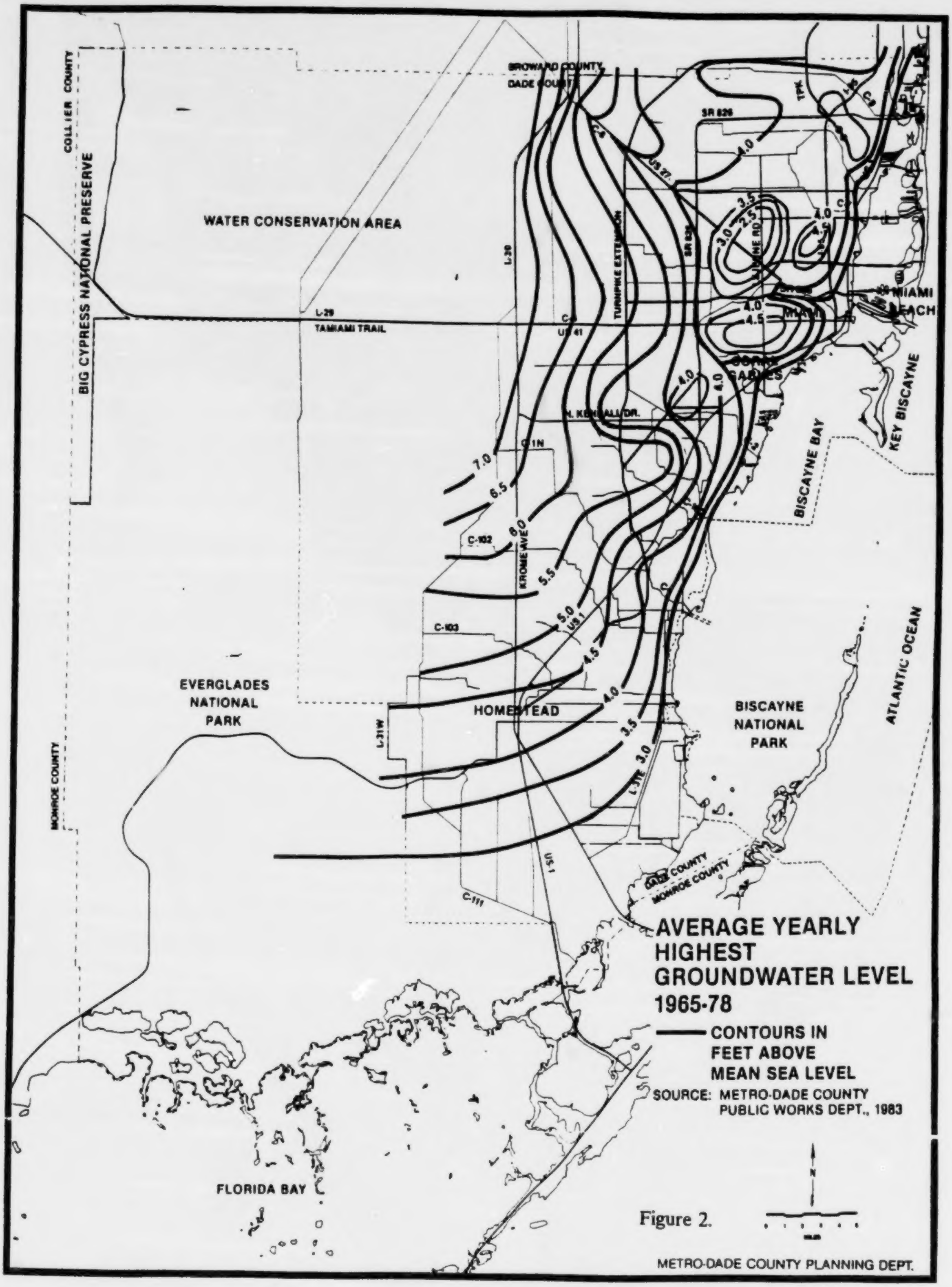
As Figure 1 shows, today most of Greater Miami is on lower ground. It was made habitable through drainage and reclamation (Metropolitan Dade County Planning Department, 1979). Water drainage from the Kissimmee River basin and Lake Okeechobee begins northwest of Miami and runs through canals to Miami and other coastal cities. Also to the northwest are three water conservation areas used in the South Florida water management system. South and west of the inhabited area is the Everglades National Park, a unique ecology. On the east, Miami is bounded by the Biscayne Bay and the Atlantic Ocean.

Just a few feet below Miami's surface lies the Biscayne aquifer, the major freshwater supply for the area. Maps in the Dade County Comprehensive Plan show that the height of the water table varies by about 3 feet between seasons, but always exceeds sea level in most of the aquifer. Figure 2 shows the average annual highest level of water in the aquifer. A comparison of Figures 2 and 3 reveals that the water table is very close to the surface except along the high points of the Atlantic Ridge. In the wet season, water flows less than 5 feet below 34 percent of Miami streets (measured by Dan Brenner, Assistant Highway Engineer, City of Miami Department of Public Works, 1988).


Tamiami Trail
79 St. Causeway
Julia Tuttle Causeway
MacArthur Causeway
Rickenbacker Causeway
BISCAYNE BAY
ATLANTIC OCEAN
1
2
3
ELEVATION ABOVE MEAN SEA LEVEL
▇ > 15
▨ 10 - 14.9
▇ 5 - 9.9
░ < 5

TOPOGRAPHY

Figure 1. Miami Topography.


COLLIER COUNTY
BIG CYPRESS NATIONAL PRESERVE
WATER CONSERVATION AREA
BROWARD COUNTY
DADE COUNTY
SR 826
TPK
US 27
L-30
TURNPIKE EXTENSION
SR 826
L-29
TAMIAMI TRAIL
US 41
MIAMI
MIAMI BEACH
CORAL GABLES
N. KENDALL DR.
C-1N
C-102
C-103
KROME AVE
US 1
L-31W
L-31E
C-111
HOMESTEAD
EVERGLADES NATIONAL PARK
MONROE COUNTY
BISCAYNE BAY
KEY BISCAYNE
BISCAYNE NATIONAL PARK
ATLANTIC OCEAN
DADE COUNTY
MONROE COUNTY
FLORIDA BAY
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
N

AVERAGE YEARLY HIGHEST GROUNDWATER LEVEL 1965-78

CONTOURS IN FEET ABOVE MEAN SEA LEVEL

SOURCE: METRO-DADE COUNTY PUBLIC WORKS DEPT., 1983

Figure 2.

METRO-DADE COUNTY PLANNING DEPT.

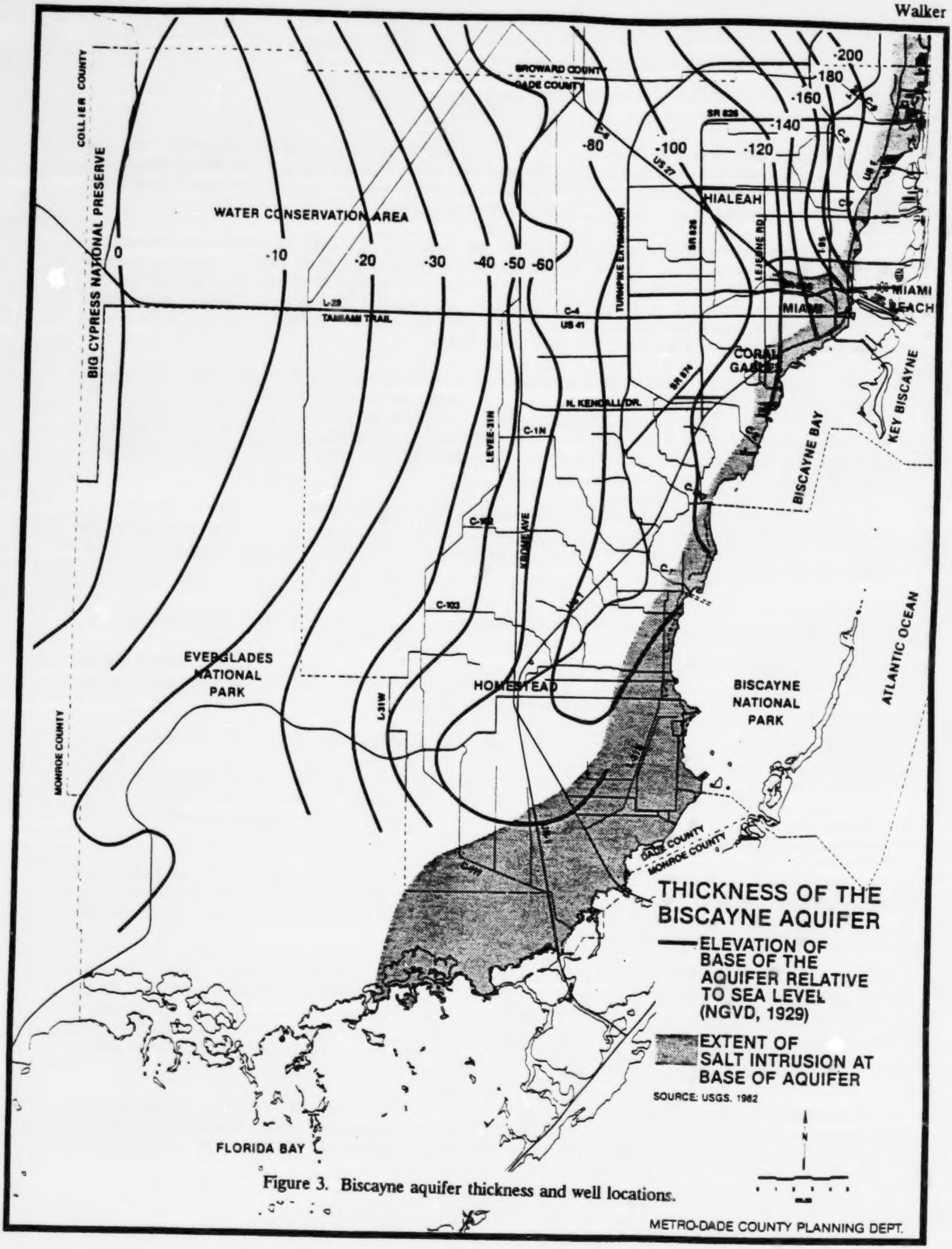

COLLIER COUNTY
BIG CYPRESS NATIONAL PRESERVE
BROWARD COUNTY
DADE COUNTY
WATER CONSERVATION AREA
0
-10
-20
-30
-40
-50
-60
-80
-100
-120
-140
-160
-180
-200
SR 826
US 27
HIALEAH
TURNPIKE EXTENSION
LEJEUNE RD
I-95
US 1
L-29
TAMIAMI TRAIL
C-4
US 41
MIAMI
MIAMI BEACH
CORAL GABLES
SR 874
N. KENDALL DR.
C-1N
LEVEE-31N
KROME AVE
C-102
C-103
BISCAYNE BAY
KEY BISCAYNE
EVERGLADES NATIONAL PARK
HOMESTEAD
L-31W
MONROE COUNTY
BISCAYNE NATIONAL PARK
ATLANTIC OCEAN
DADE COUNTY
MONROE COUNTY
C-111
FLORIDA BAY
THICKNESS OF THE BISCAYNE AQUIFER
ELEVATION OF BASE OF THE AQUIFER RELATIVE TO SEA LEVEL (NGVD, 1929)
EXTENT OF SALT INTRUSION AT BASE OF AQUIFER
SOURCE: USGS. 1982
N
METRO-DADE COUNTY PLANNING DEPT.

Figure 3. Biscayne aquifer thickness and well locations.

As Figure 3 illustrates, the Biscayne aquifer is wedge-shaped. It is 100 to 200 feet deep along and below Biscayne Bay and averages 100 feet in depth in the developed area. West of the city, it falls off rapidly and ends near the Dade County line. Because of the aquifer's shape, much of the water only can be tapped by wells dug in or just west of Miami. Figure 4 shows current public well locations.

As indicated in Figure 3, the seaward edge of the aquifer is saltwater. In many cases, the cone of depression for the wells comes close to the salt line in the dry season. Since the 1940s, Miami has used freshwater pressure to prevent further saltwater intrusion into the aquifer. Currently, control structures and canals are used to create a 2- to 3-foot head differential (Metropolitan Dade County Planning Department, 1979). This results in saltwater intrusion from 0.25 to 2 miles inland in the developed areas and about 5 miles in the Everglades National Park where the aquifer is shallower.

The Biscayne aquifer is one of the most permeable in the world, an extraordinarily transmissive layering of sand, solution-riddled limestone, and sandy limestone roughly 100 times more permeable than packed sand (Metropolitan Dade County Planning Department, 1979). Wellfields are recharged simply by channeling water across the aquifer and letting it percolate down (South Florida Water Management District, 1987). The height above sea level and groundwater discharge areas of the aquifer change constantly in response to such relatively minor factors as rainfall and tides (Metropolitan Dade County Planning Department, 1979).

Because of Miami's high temperatures, reduced evaporation loss makes the Biscayne aquifer a much better place than shallow surface lakes to store water for use in the dry season (Metropolitan Dade County Planning Department, 1979). Furthermore, overuse of surface storage would destroy the unique Everglades ecology, which requires cyclic drying.

THE POROUS AQUIFER MEANS DIKING ALONE WILL NOT CONTROL SEA LEVEL RISE

In most coastal communities, the major challenge of a 3-foot rise in sea level is to control surface inundation. The solution in both New Orleans and the Netherlands has been to dike the water at the surface and pump out the modest seepage into ditches behind the dikes.

To do this in Miami, one would have to construct a dike that holds water back for the entire depth of the Biscayne aquifer. Essentially, one would have to construct a water-impermeable barrier along the length of Broward and Dade Counties to a depth of 100 to 150 feet. Otherwise, the pressure of the seawater merely would cause the sea to rush into the aquifer below the surface and push the freshwater in the aquifer up 3.3 feet, very close to the surface. If one pumped the freshwater out, it gradually would be replaced by saltwater and the freshwater storage capacity of the aquifer would be lost.

A very preliminary analysis suggests a two-pronged approach. One prong is to raise the land in low areas rather than trying to dike. The second is to increase the freshwater head roughly in proportion to sea level rise, thus maintaining the freshwater storage capacity of the aquifer. This method will not raise the water table notably more than sea level rise alone.

Thus, if sea level rises 3.3 feet, Miami could raise its freshwater head by 2 to 3 feet to control subsurface seawater infiltration into the aquifer, as well as by raising or building surface levees and adding pumping capacity in developed low-lying sections. Even this approach may not work because the necessary water simply may not be available, especially during droughts. According to the Dade County master planning staff, Miami will face a water supply deficit in the 21st century. The most practical solutions appear to be purifying sewage effluent or desalinating water at three times the cost.

A detailed examination of the issues and options is needed. For the purposes of this report, consistent with Rhoads (1987), we have assumed that selective retreat, levees with pumped outflows in selected low-lying areas, and elevation of some facilities and structures, as well as an increase in the freshwater head to protect the aquifer, will prove to be the most cost-effective solution on the mainland. Information about the appropriate intervention for Miami Beach and other developed barrrier islands, primarily beach nourishment, is given in Leatherman (1989).

OCEANGATES WILL NEED UPGRADING

Dade County's water management system includes an extensive network of oceangates -- about 600 miles of canals, 200 miles of levees, and 30 control structures (County Planning Department, 1979). The canals probably will not require rebuilding, but probably will have to be dredged more frequently. The levees probably will have to be raised in selected areas, which can only be identified through detailed studies. Robert Hamrick at the South Florida Water Management District estimates it would cost approximately $15,000 per linear mile to raise the levees 2 feet with mounds of crushed limestone, which is extensively quarried locally in open pits. The fill is scooped from a copious supply lying virtually at the surface on public lands, then loaded on flat-bottomed barges and sprayed onto the tops of the levees. Interpolating from the analysis in Weggel (1989), we estimate that $60 million would be spent on canal and levee improvements if sea level rose 3.3 feet over the next 100 years. Hamrick also suspects that the 30 control structures in Dade County would have to be redesigned and replaced at an estimated cost of $1.6 million each, a total of $48 million in 1988 dollars.

The current water management system relies mainly on gravity drainage. With sea level rise, much pumping capacity would have to be added to prevent subsurface saltwater intrusion. Both the capital and operating costs would be large.

WATER SUPPLY WILL BE REDUCED UNLESS HURRICANES INCREASE

Miami's water supply will be reduced by water use to prevent saltwater infiltration. Some wellfields almost certainly will have to be relocated further inland. Potentially, more important than the actual water expenditure, the aquifer will rise closer to the surface, putting it in easy reach of the roots of more plants. Using evapotranspiration and soil moisture models, Rhoads (1987) estimates that soil moisture deficiency probabilities will double due to the 5°F rise in average temperature associated with an effective doubling of carbon dioxide, assuming no change in rainfall.

Water supply will be adversely impacted by temperature-related evaporative water loss in the water conservation areas. Furthermore, temperature rise will increase cooling degree days by roughly 2000, about a 50 percent rise. That means more water consumed for air-conditioning, agriculture, and urbaculture, i.e., gardening in yards and parks. To make matters worse, an effective doubling of carbon dioxide is likely to reduce rainfall in the dry winter months from the current 1.9 inches a month to 1.6 inches according to the GISS model or 1.7 inches according to the GFDL model (Jenne, 1988).

The solution to these problems will require detailed study. One alternative is increased capacity to produce desalinated water -- e.g., by boiling and cooling, reverse osmosis filtration, or some new technology -- or to use purified effluent as a backup supply for drought periods. Full cost pricing of this water should encourage greater conservation, reducing demand. Another complexity requiring study is the need to maintain some water in the water conservation areas, since the water containments are designed to function with a vegetative lining.

The largest uncertainty about water supply is the impact of climate change on hurricanes. Hurricanes historically have contributed substantially to aquifer recharge (Metropolitan Dade County Planning Department, 1979). Rising temperatures could increase hurricane frequency and intensity. This would be a mixed blessing, assuring an adequate water supply but inflicting billions of dollars in wind and flood damage.

BUILDING FOUNDATIONS ARE ADEQUATE

A preliminary examination of structural stability of footings and pilings suggests that buildings are not likely to suffer structural instability from a 3.3-foot rise in the water table. When a building is on coral rock or limestone, concrete footings with reinforcing steel frequently provide structural support. A monolithic slab with flared ends to a depth of 18 to 24 inches is a typical foundation for a residence, since most residential structures and commercial buildings are too close to the water table to have basements. Larger residences might have both seatings and footings. Tall buildings including residential condos are most likely to rest on piles, although other techniques are used to provide structural support including spread footings and compacting.

Flooding raises little possibility of structural instability due to settling, foundation cracking, and so forth, because the foundations are overdesigned by a factor of 1.5 to 2.0, according to engineers at Florida Atlantic University.

Regulations and permitting procedures, including Dade County Flood Criteria and those of the National Flood Insurance Program, require most new construction to be on raised lots to prevent flood damage. These regulations and permitting procedures will need to be modified to protect new buildings and other types of infrastructure in areas that sea level and water table rise will make vulnerable to more severe flooding.

ONE-THIRD OF THE STREETS WILL NEED TO BE RAISED

A typical city street consists of a 1.5-inch layer of asphalt constructed over an 8-inch limerock base. Beneath the base is a subgrade, with its top 6 inches compacted to a minimum of 95 percent of its maximum density. If the sea level and water table rose roughly 3.3 feet, given the annual fluctuations in the water table and its proximity to the surface, the subgrade and/or base of many city streets would be subject to a certain amount of saturation. This could cause complete structural failure if a heavy load were to pass over the surface. To prevent this, vulnerable streets would have to be raised by 3.3 feet.

Dan Brenner of the City of Miami Department of Public Works estimates that approximately 34 percent of street and highway mileage -- 257 miles -- is 5 feet or less above the water table. Raising streets by 3.3 feet during reconstruction, according to the Department of Public Works, would raise reconstruction cost from $150 to $175 per linear foot (remember that fill is cheap) with minimally improved transitions to adjacent properties. The cost of reconstructing the 257 miles to adjust for a 3.3-foot rise in sea level would be roughly $237 million. Omitted from this cost estimate are substantial private costs that will be incurred for better drainage, raising of some yards (especially at newer buildings where the structure itself already is raised), raising lots at reconstruction, and positive sewage pumping from the houses to the mains in some areas.

The aesthetic drainage impacts of this change will be dramatic. Except recently constructed houses, which often are raised to meet flood ordinances, people's houses, yards, and garages would be 3 feet below the streets (and canals), a situation strongly reminiscent of the Dutch countryside. Imagine standing in your front yard and looking up at the street. Undoubtedly, some yards and houses will be raised when they are reconstructed, and yards are likely to be raised or flanked by covered exfiltration trenches. Fortunately, there are no basements.

The projected rise in temperature should have negligible impact on streets and highways, since asphalt pavement withstands substantial temperature variations.

MANY CAUSEWAYS AND BRIDGES SHOULD BE RAISED AT RECONSTRUCTION

The causeways running from Miami across Biscayne Bay to Miami Beach are between 5 and 10 feet above sea level and might be at risk of structural weakening and failure. They would also be vulnerable due to the increased size of hurricane storm surges. These potential impacts could be avoided with reconstruction over the next 100 years involving design features to mitigate the effects of the sea level rise. Except for steel drawbridges, most bridges in Miami are constructed of concrete and steel, with a life expectancy of 50 years. Only those near the coast have epoxy coated reinforcing bars, a practice introduced in 1970 to fight corrosion. Without remedial action, the effects of sea level rise will include:

- Pavement failure in low-elevation bridge approaches.
- Erosion beneath low-lying bridge abutments and consequent differential settlement, stresses, and strains.
- Potential lifting of corrugated steel and box culverts.
- A drop in the elevation of fenders on the piers over navigable waters. Fenders protect against damage from vessels bumping into the substructure.
- Reduced underclearances on navigable waterways.
- Reduced accessibility inhibiting proper inspection and maintenance.
- Added wave "slapping action."
- Increased likelihood of flood backwaters, particularly for bridges that have underclearances of 3 to 6 feet over nonnavigable waters.

Regardless of improvements over the next 100 years, bridges with piers and piles in both Biscayne Bay and in rivers would experience deeper scouring, but the velocity in nonstorm conditions would decrease due to the increased water depth. Scouring would increase if storms became more frequent or severe.

The projected temperature increase should not cause bridge expansion outside design limits. Increased humidity, however, could accelerate paint deterioration.

AIRPORTS WILL NEED BETTER DRAINAGE

Miami International Airport is a major international hub. Located in northwest Miami, its airfields and aprons cover 7,000 acres. Unlike the majority of major commercial airports, most of the surface area is asphalt pavement. The aprons are concrete. The asphalt varies in thickness from 2 to 17 inches depending on the base. Its extensive drainage system allows storm runoff to empty into ditches by the airfield, which in turn empty into the Blue Lagoon and the Tamiami Canal. The groundwater elevation ranges from 2 to 3 feet, runways 9 to 10 feet, and taxiways and aprons 8 to 9 feet. A 3.3-foot rise in groundwater would not flood the pavement or base, but would affect drainage retention capacity and exfiltration during a storm. If several large pumping stations were constructed to draw down the airport water table at the onset of a storm, acceptable operating conditions could be maintained. Drainage interconnections and related improvements such as pump stations, dikes, and culverts might cost $30 million (Tripp, 1988).

EFFECTS ON SOLID WASTE DISPOSAL SHOULD BE MINIMAL

Dade County currently disposes of its solid wastes at a resource recovery plant with landfill, a reduction shredding facility with land fill, and a shredder pulverizer used for resource recovery. There are also three transfer stations and over 50 inactive solid waste disposal sites, including landfills and incinerators (South Florida Water Management District, 1987). Proposed expansion of solid waste disposal capacity is expected to handle growth until at least 2012, and additional staged expansion should be able to meet the solid waste disposal needs of the population until 2020 or 2030 (Downtown Development Authority, 1988). The incremental mam. disposal site selection reduces potential problems due to sea level rise.

We did not estimate the impacts of a rise in sea level on solid waste disposal. The elevations and locations of the landfill sites have not been identified as part of this study, and their current propensity to leaching under normal or flooded conditions is not fully known. Most inactive landfills, however, reportedly have already leached out. Recently constructed landfills are lined, and the active ones have sophisticated drainage and are connected to the sewage treatment system to minimize leaching.

Landfill subsidence is sensitive to temperature, moisture, the nature of waste (coarse, medium, fine), percentage of paper, whether cells are in aerobic or anaerobic condition, etc. The literature on subsidence suggests that a 5 degree temperature increase will increase subsidence by some unpredictable amount (Department of County Engineer, 1973).

SANITARY WASTE SYSTEMS WILL REQUIRE ADJUSTMENTS, PRIMARILY TO CONNECTOR PIPES

Dade County has separate wastewater and storm sewer systems. Wastewater treatment capacity has been keeping pace with population growth and business activity, increasing approximately 3 percent per year. Current capacity is 276 million gallons per day (mgd) with peak flows of 222 mgd (Downtown Development Authority, 1988). Of the three regional wastewater treatment districts, the central district has the largest capacity of 120 mgd with two sludge plants, one a high purity oxygen activated and the other a modified activated. Both the north and south districts have high priority oxygen activated sludge plants. The north district's plant has a capacity of 80 mgd and the south district's, 76 mgd.

A vast system of underground pipes carries the sewer and other processed waste to the wastewater treatment facilities from homes, commercial buildings, and industrial facilities. The largest uncertainty about water supply is the impact of climate change on hurricanes. Hurricanes historically have contributed substantially to aquifer recharge (Metropolitan Dade County Planning Department, 1979). Rising temperatures could increase hurricane frequency and intensity. This would be a mixed blessing, assuring an adequate water supply but inflicting billions of dollars in wind and flood damage.

While there have been extensive efforts to reduce infiltration, one half inch of rain during the dry season increases wastewater flow to the Central District plant by 10 to 20 mgd. During the wet season, many pipes are surrounded by water. A 3.3-foot rise in groundwater in the Miami area could significantly increase infiltration during the dry season and possibly require additional pumping capacity. A severe hurricane with flooding would produce saltwater intrusion into the sewer pipes.

Temperature increases hydrogen sulfide corrosion within sanitary sewer pipes. Due to hydrogen sulfide corrosion, the 42-inch vitrified clay pipe under the Miami River recently collapsed, releasing effluent. The fact that the pipes lie underground mitigates the effect of the surface temperature increase, so it is not clear how much more of a problem hydrogen sulfide corrosion would become.

A significant problem associated with sea level rise is that not only must streets, houses, and other buildings be raised in low-lying elevations, but also that the connectors from buildings to the sewer interceptors will require adjustments. Pump stations will have to be raised and modified to maintain the same driving force (pressure differential inside versus outside). Overflow structures would require improvements.

In the City of Miami, the costs of adapting elevated houses and other building connections to existing sewer lines would be the responsibility of private property owners. The remainder of the costs would be public. The Miami Department of Public Works estimates that the costs to raise and modify pump stations, modify overflow structures and miscellaneous appurtenances, and raise manholes alone is $8 million (in 1988 dollars).

The likely impact on one of Miami's wastewater treatment facilities, located on Virginia Key, also was assessed. Since Virginia Key has no freshwater beneath the surface, intrusion is not an issue. The treatment plants are approximately 10 feet above sea level. Berms and dikes reach elevations of approximately 13 feet, while sterile fill material from the sludge plants has accumulated to elevations around 30 feet. A severe hurricane producing higher storm surges still could wash out portions of the island. If the activated sludge treatment plants are still in operation as sea level rise accelerates, the berms and dikes on the island will have to be raised to prevent processed sludge from being washed into Biscayne Bay. Another possible effect of a hurricane is that dirt beneath the plant could be washed out, causing the piping to collapse.

Higher surface air temperatures increase bacteriological action and increase the rate at which pathogens are removed by the activated sludge treatment process. Any temperature related problems associated with activated sludge plants are likely to be easily resolved through plant modifications and improved controls.

STORM SEWERS AND DRAINAGE TRENCHES WILL REQUIRE MAJOR UPGRADING

Miami relies primarily on localized drainage and canal systems, involving exfiltration that carries surface storm water to subsurface groundwater. Highly permeable soils make this a cost-effective form of storm water drainage, except in low-lying areas where there are fine soils that do not drain well. Where natural drainage systems are not effective, and in instances where tidewaters and easterly winds increase the water head pressure at discharge outlets to the bay, a positive drainage pipe system is required.

Standards for storm sewers vary among federal, state, and local agencies. Interstate highway storm sewers are designed for 10-year storms. On arterial streets in areas of high population density, 3-year storms serve as the design standard. On local streets, Miami's system is designed for a rainfall rate of 1.5 inches per hour. Ponding will occur three or four times per year on local streets with this type of storm drainage (City of Miami Department of Public Works, n.d.).

In 1988, Miami started a 12-year, $267 million program to reduce flooding and ponding. This includes constructing 750,000 feet of exfiltration trenches at a cost of $105 million. It also includes constructing $55 million of positive drainage. These systems are designed to provide protection against flooding from 25-year storms (Department of Public Works, 1986).

Even with these planned improvements, if sea level rises 3.3 feet, flooding and ponding problems probably would be worse than they are today, especially because the water table will be closer to the surface. The costs of adequate future flood protection almost certainly will be several hundred million dollars.

HURRICANES WILL INFLICT MORE SEVERE DAMAGE

Miami has not experienced a direct hit by a major hurricane in 55 years. When it does, more than 400,000 people will have to be evacuated. The developed barrier islands -- Miami Beach and Key Biscayne -- and portions of the mainland will be hit by a 15-foot wall of water. The barrier islands will be completely submerged to a depth of at least 5 feet. Along with the surging sea will come at least 10 inches of rain (Metropolitan Dade County Planning Department, 1979). Flood control systems, which currently are being upgraded to cope with the 10- to 25-year storm, will be pushed beyond their capacity. Property losses obviously will be substantial.

The higher sea level and higher water table that will result from global climate change will increase the potential destruction, making the future effects of a moderate hurricane almost as bad as the current effects of a major one. If hurricanes also become more frequent and intense, as some experts predict, more flood control investment and a strategic retreat from the coast in some areas may be necessary.

CHAPTER 3

IMPACTS IN CLEVELAND

INTRODUCTION AND SUMMARY

Located on Lake Erie, Cleveland is prone to harsh winters and mild summers. The banks of the Cuyahoga River, which bisects the city, are lined with industrial plants.

Cleveland is likely to experience a marked change in climate over the next century. Its summer climate will be warmer, similar to current summers in Louisville, Kentucky. Its winter climate also will be much milder, rather like that of Nashville, Tennessee.

- o The GFDL and GISS scenarios project seasonal temperature increases ranging from 7 to 12°F. Winter temperatures under both scenarios are to increase about 10° bringing average temperatures above freezing. Summertime increases will be from 7 to 12° above the current 66° average.
- o The number of heating degree days will drop by about 36 percent (from a 1987 base of 6,513), but the number of cooling degree days will increase by a much wider margin (by 169 percent to 269 percent over a base of 615).
- o Snowfall is likely to be dramatically reduced with average annual accumulations declining by roughly 85 percent (from 50 inches to about 8 inches).

This case study examines the possible impacts of these changes on selected elements of public infrastructure budgets: streets and bridge decks, public buildings, the transit system, and snow removal. The results (summarized in Table 3) suggest both increases and decreases in outlays for different reasons. Costs related to public buildings and transit are likely to go up because substantial increases in air-conditioning requirements exceed likely reductions in heating expenses. The net increase in the annual space conditioning budget for public buildings, for example, could be as much as $7.1 million. On the other hand, savings can be anticipated due to less severe winters. Yearly reductions could include $200,000 due to less reconstruction and resurfacing on roads and bridges, $490,000 due to lower road and bridge maintenance requirements, and another $4.4 million due to reductions in the need for snow removal.

Given the many uncertainties involved, these estimates are far from reliable enough to support conclusions about whether the net effect will be negative or positive. They do suggest, however, that the impact will be small. A net increase of even $7.1 million, for example, would add only about one percent to today's operating budgets for Cleveland's city government and school system. In other words, the likely impacts of warmer temperatures create no demands for emergency response in Cleveland. Prudent incremental planning for capital replacement and maintenance should be sufficient to assure a smooth adjustment.

This case study also includes preliminary evaluation of another predicted change: the possibility of a 2- to 4-foot drop in the level of Lake Erie. Here again, Cleveland seems unlikely to experience serious impacts, although this change could cause navigational difficulties and other problems elsewhere in the region. Cleveland's water intakes are far enough out in the lake so that they would not be affected, and variations of these magnitudes at the shore line would not be sufficient to disturb present uses or structural conditions.

Overall, this picture represents a stark contrast to the detrimental effects of sea level rise for coastal cities like Miami and of drought and extremely high temperatures expected for many inland cities to the south. While it appears that its infrastructure conditions will not be much affected, Cleveland is likely to benefit substantially in other ways from a balmy climate and from being one of a much reduced number of American cities with an ample freshwater supply. An image change from "rust belt" to "garden spot" is not an outlandish prediction.

TABLE 3

ESTIMATED IMPACTS OF A DOUBLING OF ATMOSPHERIC CARBON DIOXIDE ON CLEVELAND'S ANNUAL INFRASTRUCTURE COSTS
(Millions of 1987 Dollars)

Cost Category	Annual Operating Costs
Heating	-2.3
Air-Conditioning	+6.6 to 9.3
Snow & Ice Control	-4.5
Frost Damage to Roads	-0.7
Road Maintenance	-0.5
Road Reconstruction	-0.2
Mass Transit	summer increase offsets winter savings
River Dredging	+0.5
Water Supply	negligible
Storm Water System	negligible
Total	-1.6 to +1.1

CLEVELAND'S INFRASTRUCTURE CONDITIONS

Population and employment losses in Cleveland in the 1960s and 1970s took their toll in the form of a stagnating tax base and cuts in municipal expenditures. This was reflected in the condition of the area's infrastructure, which by reputation and some objective measures was in worse condition than that of most other U.S. cities of comparable size. In the early 1980s, however, local governments in the area banded together in a campaign to address these problems (Peterson et al., 1982). The task is far from complete (the area's total capital need for roads and bridges, transit, water supply, and sewers for the 1988-1992 period is estimated at $1.2 billion), but investment has gone up considerably over the past few years and the campaign has been successful in raising more local as well as state and federal funds for these purposes (Walker and Friedman, 1988). Thus we judge that the area has much better than average institutional preparedness to deal with any additional infrastructure demands motivated by climate change.

IMPACTS ON ROADS AND BRIDGES WILL BE POSITIVE

Like most cities, Cleveland maintains an extensive road and bridge network: some 1,550 miles of road and 93 bridges with a total surface area of 1.8 million square feet (Parham, 1985). By some measures, Cleveland's road and bridge stock is in poorer condition than is typical for U.S. cities. Among 34 cities with road condition data readily available for 1983, Cleveland road mileage ranked last in the percentage rated as "good" (5.6 percent) as opposed to "fair" (91.8 percent) or "poor" (2.7 percent) (Peterson et al., 1981).

Similarly, the city's bridges included on the Federal bridge inventory are in relatively poor condition. Among 62 major U.S. metropolitan areas in 1980, the Cleveland area ranked 12th in its share of structurally deficient bridges: 23 percent of the areas's 279 bridges fit this category. Indeed, among the 93 bridges for which the city has sole maintenance responsibility, 75 are structurally deficient by the Federal Highway Administration definition (Peterson et al., 1981).

The deteriorated state of the city's transportation infrastructure is the combined product of environmental and budgetary factors (Bowersock, 1988; Getz, 1988). Years of underfunded capital programs and deferred maintenance contributed to the need for major capital renewal. Nevertheless, engineers responsible for road and bridge design attribute a large share of the blame for poor road pavement and bridge deck performance to environmental factors: moisture and temperature effects in the former case; use of salt in deicing efforts in the latter.

Low-Temperature Damage To Roads and Bridges Will Be Reduced

The most serious low-temperature effect on flexible (e.g., asphalt) pavement performance is frost heaving, which occurs when free water in the roadbed soil collects and freezes to form ice "lenses" (American Association of State Highway and Transportation Officials (AASHTO), 1987). The accumulation of thickness from these lenses causes localized heaving of the pavement surface during extended frozen periods. The principal variable affecting the amount of heave that occurs is the depth of frost penetration, which is directly correlated with the number of consecutive low-temperature days. The amount of heave, and hence the potential loss in serviceability, also is affected by the quality of drainage.

Currently, the mean annual number of days with maximum temperatures below freezing is 46. According to local highway engineers interviewed for this report, these subfreezing days, on average, produce about five to six deep freeze/thaw cycles annually. Under both the GISS and GFDL scenarios, the number of days below freezing, and hence the estimated number of cycles, will decline dramatically over the coming century. The GISS scenario results in a mean annual number of days with maximum temperatures below freezing of 13, roughly a quarter the total mean number of days currently. If the number of days below freezing are taken as a proxy of the number of freeze-thaw cycles to be expected per year, 75 percent fewer days below freezing produces an estimated 1.5 deep freeze cycles per year. City engineers estimate the current depth of frost penetration for bare pavement at 4 feet, with good drainage. Applying these factors in the AASHTO equations yields an improvement in the serviceability index value for Cleveland of 11 percent.

An alternative approach that suggests impacts of a roughly similar magnitude is the Moisture Accelerated Distress (MAD) Index, which classifies subsoil and drainage types for geographic regions across the nation according to their potential for abetting "pavement distress" attributable to environmental factors (Carpenter et al., 1981). Pavement distress is observable in the cracking of flexible (largely asphalt) or rigid concrete pavements, frost heave of flexible pavements, or joint failure or spalling of rigid pavements.

The MAD Index is based on the interaction of four factors: temperature, moisture, roadbed material, and drainage. The last two factors, as defined in the Index, will be little affected by climate change. City highway engineers rate the typical subgrade in Cleveland as "moderately drained," and the granular layer as "free draining." Whatever improvement in drainage is attributable to lake level drop will not produce a shift in broad drainage categories.

The GFDL and GISS scenarios suggest that temperature and moisture changes attributable to global climate warming will produce winter conditions in Cleveland roughly akin to those prevailing today in Nashville, Tennessee (estimated from Kalkstein, 1988). This will produce a change in temperature zone, for purposes of calculating the MAD Index, resulting in an approximate 7 percent decrease in potential for moisture-accelerated damage.

Another impact to be considered is design requirements for new or replacement road surfaces. AASHTO has defined a Regional Factor for use in the design of roadways using flexible pavements (FHWA, 1983). This factor essentially is a summary measure of adverse weather conditions. It is used to weight the axle-load factor used to determine asphalt pavement thickness. This factor ranges from 0.5 in the far Southwest to a U.S. mean value of 1.7 to a maximum value of 3.5 in northern Minnesota. The Cleveland area value is 1.5. With an increase in mean temperature, and using Nashville as Cleveland's winter analog, the value for Cleveland would drop from 1.5 to 1.0. This change results in a 7.5 percent decline in the required thickness of asphalt overlay in roadway construction.

Maintenance Costs Will Be Reduced About 10 Percent

Roughly estimated, the amounts to be saved in road and bridge repair costs as a result of decreased pavement and bridge deck stress are modest, but not negligible. Currently, Cleveland spends about $4.9 million per year on street repair: filling potholes, cracks, and other surface defects. An additional $100,000 is expended on bridge deck repair (Parham, 1985). This amount is almost entirely devoted to routine pothole repair, filling of joint and other surface cracks, and other maintenance activities associated with routine treatment of ordinary surface wear and tear.

Roads. As seen in the preceding section, the change in the present Serviceability Index due to frost heave is an estimated 7 percent. The estimated MAD Index change, accounting for all sources of moisture-accelerated distress including frost heave, is 11 percent. If these changes are correlated with actual incidence of pavement damage, then a conservative estimate of savings due to reduced damage frequency is roughly 10 percent or $490,000.

Bridges. The city performs only emergency repair on bridges. City engineers indicate that of an average annual bridge maintenance budget of about $1 million, about 10 percent is expended on the repair of bridge decks, the remainder supporting maintenance of lift bridge mechanisms (Browersock, 1988). Though some deterioration of bridge decks can be attributed to the effects of temperature and moisture alone, these effects are minimal compared with the use of road salts. With milder winters meaning sharply reduced snow and ice control efforts, far less corrosive salt will need to be spread on the area's bridges. Nevertheless, we judge that negligible economic benefit will be credited to this development since new techniques in bridge construction, principally the use of epoxy-coated reinforcing steel as a means of preventing contact between the bare steel and deicing salts, should reduce corrosive impacts long before milder winters become the norm (Virmani, et al., 1983).

Capital Costs Will Drop 1 to 3 Percent

AASHTO design guidelines, including the regional factors used in the flexible pavement design equation, represent the best way of estimating changes in capital costs attributable to climate change. The expected change in winter temperatures, using an analog of Nashville, Tennessee, means a reduction in the AASHTO Regional Factor from 1.5 to 1.0. Based on the equations developed in FHWA (1983), each unit change in the Regional Factor produces a 13 percent change in the structural number (thickness) of flexible pavement. For roadway construction or reconstruction jobs, roughly 26 percent of total construction costs are attributable to pavement costs. Of this figure, 70 percent of costs are variable with thickness. Therefore, 18 percent of total construction costs are potentially affected by weather (26 percent X 70 percent). Thus, a change in the Regional Factor from 1.5 to 1.0 on roadway reconstruction jobs means a drop in total costs of approximately 1 percent.

Resurfacing jobs, however, contain a higher percentage of pavement costs to total job cost than do reconstruction jobs -- approximately 60 percent. Using the 70 percent of costs that are variable with thickness, as before, 42 percent of total resurfacing costs can be viewed as weather-influenced. If a 0.5 drop in the Regional Factor means a 7.5 percent change in structural number, then total cost reductions on resurfacing work are estimated at 3 percent.

Table 4 presents Cleveland's road resurfacing and reconstruction costs for 1983-1987. Assuming that the city's capital investment levels change proportionately over time and that the climate-adjustment factors are approximately correct, a 5-year estimated saving of about $1 million can be expected on a total budget of $76 million.

TABLE 4

CLEVELAND ROAD RESURFACING AND RECONSTRUCTION OUTLAYS 1983-1987 (Dollars in Thousands)

Year	Reconstruction	Resurfacing	Climate-Savings
1983	$5,184	$1,930	$110
1984	6,233	2,179	127
1985	5,334	2,391	124
1986	26,544	2,166	330
1987	21,913	2,166*	284
Total	$65,208	$10,832	$977

Notes: * = Estimated. Climate change savings are computed as 1% of reconstruction costs, 3% of resurfacing costs.

Source: Compiled by The Urban Institute based on unpublished material supplied by the City of Cleveland Budget Office (1987 figures), and data from the Mayor's Estimates, 1983-86.

ENERGY COSTS IN PUBLIC BUILDINGS PROBABLY WILL RISE

Cleveland has 254 public buildings with a total of 19.4 million square feet of floor space. This count includes only facilities used by the City of Cleveland (owned and rented) and the Board of Education and, as such, is not all inclusive (e.g., universities, hospitals, public housing, and state and federal offices are excluded). Nonetheless, it encompasses most buildings of relevance. As in most cities, the nonresidential public building stock is dominated by education facilities (accounting for 70 percent of all floor space).

The increased winter and summer rainfall predicted for Cleveland should have no measurable impact on the operation of public buildings themselves. The substantial declines in snowfall and freeze-thaw events that are anticipated should have some positive effects (less snow shoveling to maintain access, some reduction in structural deterioration and thus maintenance), but we judge that those effects will be too small to warrant analysis in this context. Temperature change appears to be the only long-term outcome that could have notable impacts on buildings. As noted earlier, the annual number of heating-degree days is expected to decline by about 35 percent and the number of cooling-degree days may expand to 2.7 to 3.6 times the present level.

Comprehensive data on existing space conditioning systems in Cleveland's public buildings are not available. Nonetheless, interviews with those responsible for property management offer enough evidence to support basic judgments about impacts.

The Capital Costs of Heating Systems Should Not Be Affected

As would be expected given Cleveland's present climate, all of the buildings in the inventory have heating systems. There is considerable variation in system types, ages, and energy efficiencies. Assuming a 30-year replacement cycle, these systems will be replaced at least three times on average over the next century. In many cases, installation will take place as a part of the construction of new buildings that replace structures in the existing stock that are demolished or converted to other uses.

The stream of replacement outlays seems unlikely to be altered noticeably one way or the other by the climate change scenarios discussed here. Even though Cleveland's winters will be much milder on average, all buildings will still need heating systems that produce adequate warmth on very cold days. Thus basic capacity requirements will not change. Although systems will not have to operate as many hours per year, interviews with space conditioning engineers suggest that those effects will not alter replacement rates significantly.

More Buildings Will Require Air-Conditioning

Climate change could make more of a difference in air-conditioning capital requirements, although not as much as might be supposed. No cost will result from replacing units in buildings that are presently air-conditioned. Most air-conditioning equipment now in place was built with sufficient capacity to handle very hot weather, even though it does not occur very often in Cleveland at present. More hot days will simply imply longer hours of operation -- not changing capacities.

The only possible difference of note for air-conditioning capacity would be the one-time capital cost of providing systems to buildings that are now without service altogether. These include roughly 65 percent of Cleveland's schools and large "nonoffice" spaces in other facilities, including repair spaces in garages and gyms in recreation centers.

The costs of installing new systems in these spaces would vary dramatically with conditions of the structures involved. Accurate estimates are clearly beyond the scope of this study. To get some sense of the order of magnitude, we assumed that systems would be required for 90 buildings averaging 90,000 square feet in size and asked space conditioning engineers to estimate a rough typical cost. The results ranged from $720,000 to $900,000 per building, from $65 million to $81 million in total. These amounts represent 28 to 34 percent of the combined city and Board of Education capital budgets for 1988, but outlays would of course be spread over a long period. Also, the per building cost would probably be reduced by 5 to 20 percent where air-conditioning is provided as a part of the construction of new replacement buildings rather than being installed in existing structures.

Much of this expenditure might be made even without the temperature increases resulting from increasing atmospheric carbon dioxide. As air-conditioning costs have declined over the past few decades, coverage has expanded dramatically. Most notably, if the Cleveland system adopted the frequently heard proposal for more intensive, year-round use of school facilities, pressures to provide comprehensive air-conditioning would be very strong regardless of expected climate change.

Operating Costs Should Rise 50 to 90 Percent

Since the early 1980s, the City of Cleveland has implemented a program to improve the energy efficiency of city operations (City of Cleveland, 1982). Their baseline analysis showed that the city spent $33.2 million for energy in 1981 -- 15 percent of the total general fund expense budget for that year but second only to personnel costs in size among major categories of expenditure. Of the energy total, $8.2 million (one fourth) went for lighting, space conditioning, and other uses in public buildings. As one outcome, the program has begun fairly careful tracking of energy use in its facilities.

Unfortunately, the data do not isolate the costs of heating and air-conditioning per se, but they offer a basis for some rough estimates. For city buildings, we assumed that 15 percent of all electricity use goes for air-conditioning and all of the costs of steam, and 65 percent of the costs of natural gas goes for space heating (estimates derived from partial data and judgments by Cleveland's Energy Office). For Board of Education facilities, we assumed the same distribution of energy use per square foot as for city offices and the same percentage allocations to heating and air-conditioning.

Under these assumptions, current annual costs for space conditioning would be about $8.5 million ($6.7 million for heating and $1.8 million for air-conditioning). An additional $1.3 million would be spent for cooling at present if all buildings had air-conditioning equipment.

We next assumed that the changes in heating and air-conditioning energy use and costs over the next century will be proportional to the projected decreases and increases in heating and cooling degree-days. Assuming further that all schools would be air-conditioned by then, the changes from current expenditure levels would be as follows:

	Cooling-Degree-Days Est.	
	GISS	GFDL
Reduced heating cost	($2,300,000)	($2,300,000)
Increased air-conditioning	5,300,000	8,000,000
Net increase	$3,000,000	$5,800,000

Assuming no efficiency or price changes, annual expenses for space conditioning would increase from $8.5 million to between $12.8 million and $15.6 million in 100 years. The largest difference ($7.1 million), however, represents only about one percent of the combined City General Fund and Board of Education expense budgets for 1988. The gap in these estimates occurs largely because air-conditioning relies solely on electricity, which currently has a per BTU price about three times the average for steam and natural gas.

IMPACTS ON TRANSIT SHOULD NOT BE SIGNIFICANT

The Greater Cleveland Regional Transit Authority (RTA) operates a fleet of 815 buses and 207 railcars that carry over 88 million passengers per year.

Air-Conditioning on Transit Vehicles Has Minimal Cost

Analysis does not suggest any significant impact on RTA capital costs due to climate change. Neither the rail nor the bus fleets now have special equipment mandated by snow conditions that could be eliminated (and thus save costs) in subsequent replacements. All vehicles are equipped with heating systems, which will still be needed. All rail cars have two 7-ton air-conditioning units. These should have adequate capacity to handle much longer hot weather seasons and RTA staff suggest that, if anything, more regular use would probably improve their operation since lubricants would circulate more effectively.

None of the Cleveland buses are presently air-conditioned, so equipment would probably have to be added in this category at some time over the coming century. However, given an estimated average 10- to 14-year replacement cycle and considering the expected pace of temperature increases, there would be no justification for accelerating replacements on these grounds alone. Also, the American Public Transit Association indicates that most buses now being sold are equipped with air-conditioning and that the percentage continues to increase. Price differentials for buses with and without such equipment are already small and are narrowing. Therefore, it appears that adding air-conditioning for Cleveland area buses during regular bus replacement cycles over the next century would not have a notable effect on total capital outlays.

Savings in Snow-Related Operating Costs Will Offset the Cost of Fuel Used For Air-Conditioning

Similarly, while climate change will alter RTA operating costs, our interviews suggested that all effects will probably be too small to warrant quantification. On one hand, heavy snow accumulations at present do create problems, particularly for the rail system. Snowflakes that work their way into power systems can produce "flashes" (shorts) that demobilize the equipment and yield large repair bills. RTA will be able to reduce allocations for snow clearing and other outlays for prevention/correction as snow diminishes in the future. On the other hand, some increase in fuel consumption is likely to result from more frequent use of air-conditioning equipment. In relation to the overall size of RTA's $126 million expense budget for 1987, both effects will be small. Furthermore, they will offset one another.

SNOW AND ICE CONTROL COSTS WILL DROP DRAMATICALLY

As in many other northeastern cities, snow removal operations in Cleveland receive high priority from city administrators and agencies during the winter months. The Streets Division, responsible both for roadway maintenance and snow removal, maintains four stations throughout the city during summer months. Two are manned at three shifts per day, one at two shifts, and one at one shift. These stations primarily do street sweeping and repair. However, during winter months, six stations are activated, all manned at three shifts per day and all engaged primarily in snow and ice removal. Limited street repairs are undertaken throughout the winter months. The personnel used in city snow removal operations all are city employees and the equipment consists of Division of Streets vehicles.

Ordinarily, at the onset of snow or ice precipitation, the city will salt streets using employees and equipment assigned to their regular shifts. At this stage, some 45 units will be employed in salt spreading. If snow accumulates at 1/2 inch per hour, or if a 2-inch accumulation is reached, the second shift will be called four hours early, while the first shift will be kept on four hours overtime. This brings total equipment on the road to 81 salt and plow units, and 15 graders. Typically, for any storm between 4 and 12 inches over a 12-hour period, the city will average 50 to 75 vehicles for the first 12 hours, and 95 to 100 over the second 12 hours. In addition to drivers, foremen and mechanics responsible for vehicle maintenance work similar shift patterns.

The Operating Budget Will Drop Almost 2 Percent Due To Reduced Snow Removal

The annual cost of removing snow consists principally of labor costs attributable to snow removal activity, and the cost of expendable materials, such as salt, used in deicing. Table 5 presents Cleveland's annual snow removal budget for recent years, and the associated inches of accumulation. As the table shows, removal costs roughly track total accumulation.

As noted earlier, the average amount of snow accumulation projected for Cleveland under each climate change scenario is about 8 inches per year, a mere 16 percent of the current annual average. The winter comparable for the Cleveland area, Nashville Tennessee, registers average annual snow accumulation in amounts roughly equal to those projected for Cleveland.

TABLE 5

SNOW AND ICE CONTROL COSTS

Year	Cost	Accumulation
1980	$3,477	38.7"
1981	4,282	60.5"
1982	5,646	100.5"
1983	4,069	38.0"
1984	5,379	79.4"
5 Yr.Av.	$4,571	63.4"

Source: City of Cleveland Mayor's Estimates, various years; and U.S. Climatic Research Center.

Nashville snow removal costs from 1982 to 1987 averaged about $200,000 per year. Data from other cities confirm that Nashville's approximate level of expenditure is an appropriate benchmark for accumulation of that magnitude.

This implies that Cleveland's snow removal budget could decline from its current annual average of $4.6 million per year to about $200,000 per year. The decline of 95%, for an annual savings of $4.4 million, represents about 1.9 percent of the city's $235 million operating budget.

THE STORM/WASTEWATER COLLECTION SYSTEM SHOULD NOT BE ADVERSELY AFFECTED

Cleveland's combined storm and wastewater collection system presents problems for the area, primarily the effluent treatment difficulties associated with all such combined systems. (See the discussion in Peterson et al., 1982.) It does not appear likely, however, that these problems will be exacerbated by the effects of long-term climate change because both the GISS and GFDL models project decreased precipitation in the rainy season.

A DROP IN THE WATER LEVEL OF LAKE ERIE SHOULD HAVE LITTLE IMPACT

Recent analyses suggest that global warming should cause some lowering of the water levels in the Great Lakes. This would occur due to both increased evaporation from the lake surfaces themselves and increased evapotranspiration from the land, which would result in less runoff into the lakes. Quinn (1987) has worked with scenarios in which a doubling of carbon dioxide in the atmosphere yields estimated drops in Lake Erie's surface ranging from 1.7 feet to 3.5 feet. He suggests that reductions in this range would adversely impact the Great Lake system as a whole, affecting hydropower generation as well as navigation and recreational boating. Would they, however, have a notable impact on Cleveland's infrastructure?

Our inquiries, albeit preliminary, suggest that they would not, in part because the estimated drops in surface levels due to global warming would not be extreme in relation to past variations. The minimum level ever recorded for Lake Erie (in 1936) was 6.3 feet below the highest recorded level (in 1986 - Raoul and Goodwin, 1987). Seasonal variations in levels of the Great Lakes range from 1.0 to 1.3 feet, and storm surge and wind set-up can raise water levels by as much as 8.2 feet (Quinn, 1987).

With these data in mind, we asked several professionals generally familiar with relevant infrastructure elements in Cleveland if they would expect any notable costs or savings arising due to a 2- to 4-foot drop below Lake Erie's present level over the coming century. Their responses can be summarized as follows:

(1) If it occurred now, a decline in this range would be helpful in some respects. The record high water levels of the past few years are beginning to create problems in low-lying areas of the city adjacent to the lake -- problems with sewage disposal, storm-water drainage, and in some locations, shore erosion. Considering its timing, however, this impact would not eliminate the need for expenditures to address these issues in the short term.

(2) The city's water intakes are about 2 miles off shore and 20 feet to 30 feet below the lake surface, so the estimated drop would have no effect on this element.

(3) The navigability of rivers that flow through the city into Lake Erie (most important, the Cuyahoga) could be affected somewhat, necessitating dredging in some places. However, given the magnitudes and the time period involved, this would not be likely to have a notable budgetary impact.

(4) A 2- to 4-foot drop should not require the alteration of structures (predominantly piers) at the shore line.

Other factors could combine with climate effects to yield a more serious drop in the lake level over the coming century. Further analysis would be warranted if significant trends in that direction were noted.

CHAPTER 4

IMPACTS IN NEW YORK CITY

INTRODUCTION: WATER SUPPLY AND OCEANGATE NEEDS WILL BE THE LARGEST

New York City infrastructure may be affected in many ways by global climate change. Temperature change could have much the same effects as in Cleveland. The heat wave of 1988 illustrated another probable impact. In Manhattan, heat exacerbated the effects of long-standing leaks in 256 km of steam pipes, causing the asphalt to soften. As vehicles kneaded the soft asphalt, thousands of bumps formed on city streets, requiring extensive repairs (Hirsch, 1988).

Interpolation of the data in Weggel et al. (Volume B) suggests that upgrading dikes and levees in response to a 3.3-foot rise in sea level might cost $85 million over a 100-year period. A senior member of the city's Office of Environmental Protection indicated that all sanitary and much storm sewage is pumped (Schwarz and Dillard, 1988). The roughly 450 outfalls use gravity flow into tidal areas. With rising sea level, these outfalls would have to be inspected more frequently and pumps might run more, but the official felt the system capacity and design would not need revision. Higher sea level, nevertheless, could increase sewer backups, ponding, and basement flooding in a few low-lying areas when high tides coincided with high runoffs. The official noted that the city already has hedged against the possibility of sea level rise by raising an outlet on a drainage structure for a water tunnel it is building.

A study by Linder et al. (1987) suggests that increased air-conditioning use could raise peak electric demand by 10 to 20 percent in the New York metropolitan area.

The most pressing, and perhaps largest, problem facing the city may be the impacts of global climate change on water supply adequacy. Because of its complexity, the New York City case study was restricted to this issue.

The City of New York is served by one of the most extensive water supply networks in the eastern United States: a product of over 350 years of water supply planning and capital project development. Served principally by surface sources that ultimately feed estuarine waters, the city's water supply is a complex hydrologic system, dependent on the continued high quality and quantity of water in upstate watersheds, and the behavior of ocean tides in the Hudson and Delaware Rivers. It also is an extensive physical network of dams, transmission facilities, and distribution and treatment works, representing not only an enormous financial investment but also an essential component in the overall economic vitality of the region. Analysis of the city's system and speculation as to its future can lend valuable insights in water planning and management to other coastal cities in the United States.

The City of New York water supply network currently faces a modest deficit; a gap between what consumers typically demand from the system and what the system can dependably supply during drought conditions. By some accounts, this deficit is expected to increase over the next 50 years to more serious proportions as a result of population and office employment growth, continued increases in per capita consumption, and the addition of new communities to the system.

The principal effect of global climate change on the New York City water supply network will be increasing water supply deficits over those already projected as:

- rising mean temperatures and sharp increases in cooling degree days result in increased recreational and air-conditioning water use;
- increased variability in precipitation, from year to year, could produce more severe droughts, thus reducing the dependability of the existing network; and

- rising sea levels cause up-river movement of the salt front in both the Delaware and Hudson Rivers, forcing cutbacks in the amount of water that can be taken from both sources during drought.

As a result of these climate effects on the water supply network, it is highly likely that new region-wide water supply impoundments will have to be created, and new water management institutions put in place. Probable effects include:

- creation of new capital supply projects serving communities along the Delaware River Basin, Northern New Jersey, and the Lower Hudson and Long Island, at an estimated capital cost in the range of $3-7 billion;
- integration of regional communities in a single water supply and management system; and
- creation of new water management institutions at the State level to finance capital project development and allocate water among competing communities and competing uses.

WATER SUPPLY SYSTEM CHARACTERISTICS

The New York Water Supply System is in Deficit

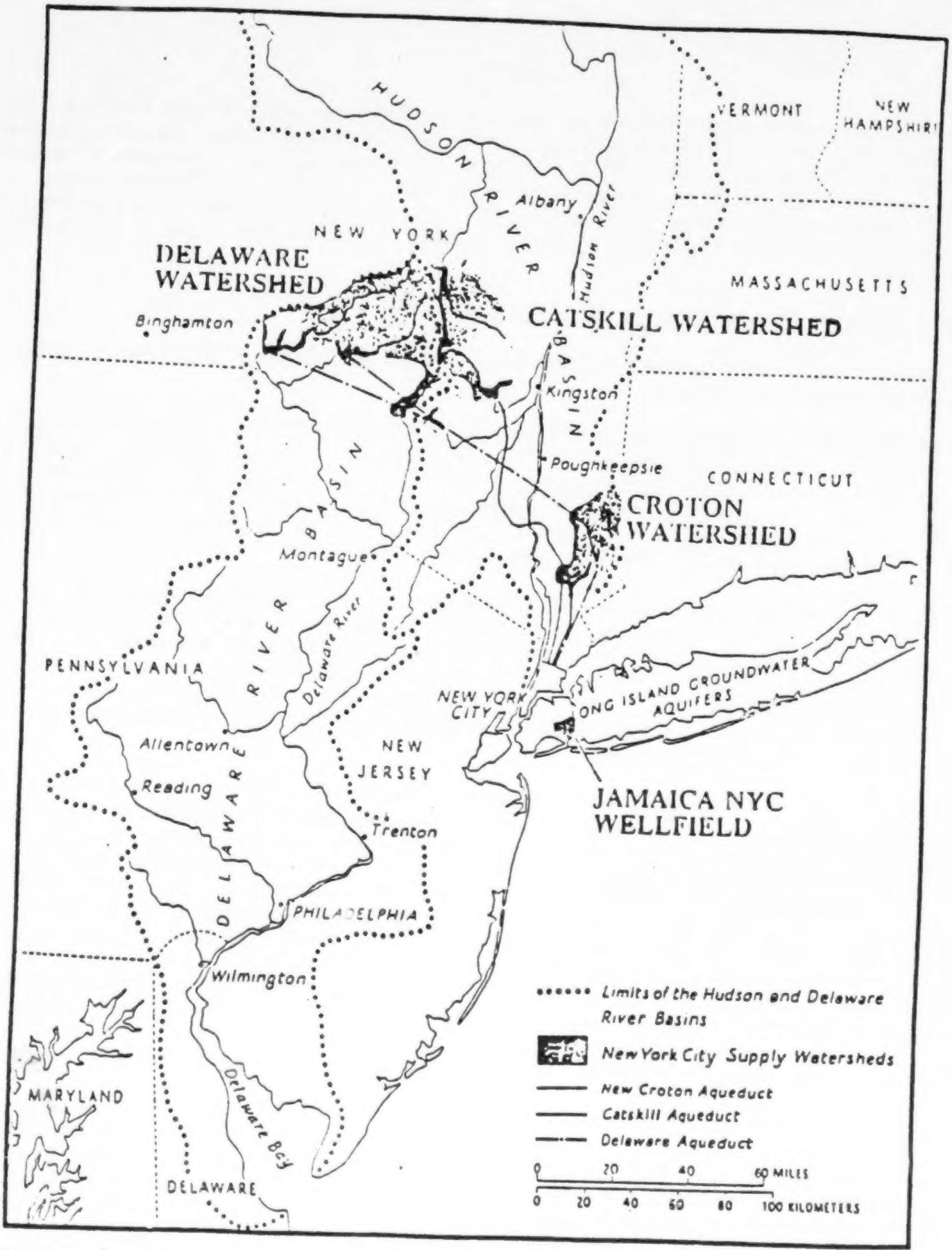
Water supply to the City of New York and those systems served by the city's water supply system is provided by four supply systems: the Delaware River Basin Watershed, the Roundout Reservoir, the Catskill System, and the Croton System (see Figure 4). With appropriate reserve capacities maintained in each system -- 25 percent for the Roundout, Catskill, and Croton reservoirs -- and the Supreme Court-mandated flow rates in the Delaware for the Delaware watershed, the system can safely supply 1,290 million gallons per day under the worst drought of record (Mayor's Intergovernmental Task Force, 1987).

This means that currently, the New York water supply network is a system in deficit. Average daily demand on the system now averages somewhat over 1,500 million gallons, meaning an approximate supply deficit of 200 million gallons (Citizens Union Foundation, 1986). In other words, if the drought of the 1960s was to be repeated, consumers in the City of New York, and in systems supplied by the City of New York, would have to cut demand by about 15 percent.

Reductions on this scale are achievable with the introduction of emergency restrictions on water consumption, but such reductions will become more difficult to effect in the future. First, water consumption will continue to increase, and second, new claimants for water from the system are likely to be absorbed into the New York water supply network.

Currently, New York City is served by two systems, the New York City System and the Jamaica Water Supply Company (WSC). These serve between 7.1 and 7.6 million people in the city (Jamaica WSC about 500,000) and another 800,000 people in upstate counties (Hazen and Sawyer, 1987). Assuming a modest increase in consumption due to population growth and no increase in per capita consumption, but allowing for new users upstate and on Long Island, an estimated 1,700 million gallons of water daily will be demanded by 2030. The currently available supply, thus, will leave a deficit of 400 million gallons daily for New York City and the other locations that the system supplies or has agreed to supply.

These projections should be viewed in the context of overall regional water supply needs: those of the Long Island communities, New Jersey, and those parts of Pennsylvania and Delaware served by the Delaware River. If current supply deficit estimates made by the Delaware Regional Basin Commission (DRBC) and those produced in support of the New Jersey Water Supply Master Plan are conservatively adjusted by a 1 percent per annum increase in consumptive use, deficits exceeding 600 million gallons per day can be projected for the Delaware River Basin communities (Hull et al., 1986) and New Jersey for the year 2030 (State of New Jersey, 1987). Plans are being made to address this deficit, as noted below.


HUDSON RIVER BASIN
VERMONT
NEW HAMPSHIRE
Albany
Hudson River
NEW YORK
DELAWARE WATERSHED
MASSACHUSETTS
CATSKILL WATERSHED
Binghamton
Kingston
Poughkeepsie
CONNECTICUT
CROTON WATERSHED
Montague
DELAWARE RIVER BASIN
Delaware River
PENNSYLVANIA
NEW YORK CITY
LONG ISLAND GROUNDWATER AQUIFERS
Allentown
NEW JERSEY
Reading
JAMAICA NYC WELLFIELD
Trenton
PHILADELPHIA
Wilmington
Limits of the Hudson and Delaware River Basins
New York City Supply Watersheds
New Croton Aqueduct
Catskill Aqueduct
Delaware Aqueduct
MARYLAND
Delaware Bay
DELAWARE
0 20 40 60 MILES
0 20 40 60 80 100 KILOMETERS

SOURCE: Citizens Union Foundation of the City of New York, Inc. Thirsty City: A Plan of Action for New York City Water Supply, 1986.

Figure 4. The sources of New York City's water supply.

New York City and the other regional water users compete for water supply from the Delaware. The Delaware River Basin Compact is the fundamental agreement structuring water allocation in the region. Backed by a 1954 Supreme Court decree, the DRBC limits water withdrawals by the New York water system to maintain a specified flow rate in the Delaware. The specified flow controls the salinity of the Delaware estuary. It preserves the habitat of current aquatic inhabitants, ensures that chloride concentrations at the Camden and Philadelphia water supply intakes do not exceed accepted standards, and prevents contamination of suburban New Jersey's aquifers.

Current Policy Responses Include Conservation and Construction

Current responses to the current and projected water supply deficits include a combination of demand management and capital project development.

Both the State of New Jersey and the DRBC (also including State of New Jersey participation) have made plans to address their current and projected deficits. Current projects already built, or on line, are expected to increase the dependable yield of the regional system by slightly over 500 million gallons per day, leaving a modest supply deficit to be addressed by projects currently being actively considered (State of New Jersey, 1987). If these projects are fully developed (all planned by the State of New Jersey under the Master Plan), the resulting yield will be more than adequate to meet projected water supply requirements.

New York City and the communities supplied by New York City currently are considering water supply alternatives to meet the existing, and projected, deficit. Demand management measures include leak detection and repair and universal metering of a now largely unmetered system. The likely result of demand management measures is unclear. The amount of water that can be saved from the repair and detection of leaks is estimated at about 25 million gallons per day. Together with the savings projected to be achieved from metering, estimated at 133 million gallons per day, about 158 million gallons per day, total, can be saved with demand management (Mayor's Intergovernmental Task Force, 1987).

This estimate, however, is unreliable, since in the absence of an already metered system, demand forecasts are very difficult to make; the actual savings may be higher or lower than indicated. And while the contribution of full-system metering to the effectiveness of local water management is clear, extreme care should be taken in projecting major savings due to metering alone. First, the price elasticity of water consumption is low; it appears to be somewhat elastic for urbaculture -- the watering of lawns and gardens -- but not very elastic for commercial or domestic consumption (Morgan and Smollen, 1976). Second, the current per capita consumption for New York City is in line with consumption in other major cities, suggesting that there is not a great deal of careless use now without metering. That part of the system currently serving New York City alone consumes about 206 gallons per capita per day (Hazen and Sawyer, 1987). This compares with survey data showing a mean per capita use of 183 gallons per day for cities over 1 million in population and is well within one standard deviation of the mean for systems of this size (Temple et al., 1982). Third, reduced discretionary water use as a result of metering will reduce the yield from emergency reductions in water use during droughts.

Proposed capital project measures include activation of the Chelsea water intake on the Hudson, and artificial recharge of the aquifer under Brooklet, currently supplying the Jamaica wellfield (Mayor's, Intergovernmental Task Force, 1987). The most likely scenario calls for reactivation of the Chelsea intake for drought emergency use, or some variant involving withdrawals at Newburgh or Kingston; from 100 million to 200 million gallons a day of added temporary capacity can be produced from this source, costing between $223 and 391 million (1986 dollars).

Assuming that demand management measures result in the water savings estimated above, and that currently considered capital projects are developed, the existing water supply deficit will be eliminated over the next 10 years.

GENERAL EFFECTS OF CLIMATE CHANGE ON SYSTEM PERFORMANCE

An effective doubling in atmospheric carbon dioxide will change the water supply balance in the region dramatically. Increased salinity in the Delaware estuary and large movements of the salt front mean that increased flows will be needed to maintain the quality of community supplies in the lower Delaware. At the same time, shifts in seasonal precipitation in the Hudson watershed will mean reduced safe yields. In addition, movement of the salt front up the Hudson River may jeopardize the viability of currently planned solutions to New York City supply problems, and saltwater infiltration into the Long Island aquifer will increase regionwide demand for surface water sources. Finally, the projected size of the New York City deficit probably will be increased by climate change-induced increases in consumption, and more uncertain supplies due to more frequent drought events.

Climate Change Will Raise Water Demand

As indicated in the first section, temperatures in the region will rise under both climate scenarios, in all four seasons. The GFDL $2XCO_2$ scenario calls for increases of 11-12°F in summer, autumn, and winter, and 8°F in spring. The GISS scenario calls for more modest increases, ranging from 6 to 8°F. If Louisville is used as the summer analog, based on summer mean, maximum, and minimum temperatures, and the number of days with maximum temperatures over 90°F (Kalkstein, 1988), the number of cooling degree days for the city will increase 21 percent, from an annual average of 1048 to a projected 1268, in response to an effective doubling of carbon dioxide.

The likely effect of this increase on water demand cannot be projected precisely. Currently, abnormally hot days can produce increases of 50 percent in the amount of water use typical for summer days. Air-conditioning use, unauthorized and authorized hydrant openings, urbaculture, and recreational use in Queens and suburban areas served by the city system all increase. Reduced summer precipitation also produces an increase in lawn watering unless usage restrictions are imposed.

The amount of increased use attributable to increased air-conditioning is difficult to estimate. Since the current water supply distribution system is unmetered, it is uncertain how much water large residential customers consume. The allocation of water use between air-conditioning and other uses also is unknown. Nevertheless, the amount of water consumed by large water-cooled building air-conditioning systems can be estimated by applying design standards to estimated climate effects on air-conditioning use. If half of the projected 800 gigawatt-hour increase in demand for electric power for air-conditioning in downstate New York due to climate change is attributed to large building systems (Linder et al., 1987), the added cooling load is about 400 million tons annually (Norman, 1988). That cooling load implies an estimated 50 million gallons per day of cooling tower water loss through evaporation (Fulkerson, 1988).

Holding the cost of water, the irrigable area, and the value of dwelling units constant, Morgan and Smollen (1976) showed water consumption for urbaculture historically has varied significantly depending on weather conditions. The largest suburban consumers of water for urbaculture are in Queens (estimated 61 mgd in 2030) and Westchester (estimated 113 mgd in 2030). Adding remaining upstate counties in the Lower Hudson Region and some Long Island communities (estimated 71 mgd), 245 mgd, or about 14 percent of total projected average daily demand, will be for urbaculture by 2030 (Hazen and Sawyer, 1987). With summer consumption averaged over the year, the additional demand, even if consumption increased 50 percent during summer months, is about 30 mgd. In sum, a rise of about 80 million gallons in average daily demand is probable. This is about 5 percent of estimated demand in 2030 without climate change.

Climate Change Will Have Detrimental Effects on Watershed Hydrology

The effect of doubled atmospheric carbon dioxide on current sources of supply is more difficult to predict, given the sensitivity of watersheds to small variations in regional climate and the difficulty of predicting the frequency of droughts.

On an annual basis, the amount of precipitation projected for the $2XCO_2$ scenario is little changed from current patterns. Nevertheless, sharp changes in the precipitation expected for certain seasons are predicted. The GFDL scenario calls for increased seasonal precipitation in all but the summer season, while the GISS scenario produces sharply reduced summer and fall amounts. Nevertheless, increased evaporation due to higher temperatures is the primary hydrologic response to climate change (Rind and Lebedeff, 1984.) The GISS and GFDL scenarios show annual declines in water runoff of about 16 and 17 percent, respectively.

TABLE 6

PROJECTED PERCENTAGE CHANGE IN SELECTED HYDROLOGIC VARIABLES FOR AN EFFECTIVE DOUBLING IN ATMOSPHERIC CO_2

Season	Precipitation		Runoff	
	GFDL	GISS	GFDL	GISS
Winter	+ 11.3	+ 4.6	+ 4.2	- 10.2
Spring	+ 7.4	+ 12.3	- 11.5	+ 10.1
Summer	- 29.7	- 4.4	- 97.7	- 22.6
Autumn	+ 11.2	- 21.7	+ 64.9	- 42.0
Annual	+ .1	- 3.3	- 17.2	- 15.8

Source: Scenarios supplied by Roy Jenne, National Center for Atmospheric Research.

Application of the water balance model developed for use in the Great Lakes region (Cohen, 1985) produces an estimated reduction in streamflow for the Great Lakes basin of between 12 and 29 percent and a supply loss of 10 to 24 percent, depending on whether reduced evaporation due to lower windspeeds will partially offset temperature effects (ICF, 1987).

Moreover, increasing variability in climate may produce more frequent droughts. Though recent research on this issue focuses on North American regions other than the Northeast, the general rule is increased variability in precipitation in higher latitudes. Average changes are from 10 to 20 percent, although these changes vary widely in magnitude across gridpoints and seasons (Rind et al., 1988). Thus, changes in precipitation may cause more droughts. Increased variability in climatic circumstances probably implies increased severity as well (Rind and Lebedeff, 1984). Therefore, the design drought probably will have to be redefined, and the system safe yield will drop.

Based on the estimated decline in net basin supply alone -- 10 to 24 percent -- the 2030 supply deficit for the New York City system will amount to about 155 to 374 mgd, assuming that current projects are completed and that savings from demand management meet projections. This estimate does not include a downward adjustment in safe yields due to increased drought severity. Substantial additional research would be required to make that adjustment.

Sea Level Rise Will Cut Safe Yields and Cause the Salt Line to Rise Above Proposed New Water Intakes

Without overstressing the uncertainty of these projections, it seems quite likely that rising sea levels over the next 100 years, based even on the most conservative projections, will have dramatic effects on supply availability from current and projected water sources.

The behavior of the saltwater interface in estuarial waters is a function of the tidal pressures acting to move the salt front upriver and the opposite flow of freshwater downriver. Under circumstances of low freshwater flows, as occurs typically during drought, the freshwater-saltwater interface moves up-river. It is precisely this phenomenon that prompted issuance of the Supreme Court decree fixing the limit of New York system withdrawals from the Delaware, in order to protect both estuarine aquatic life and community water supplies from changes in salinity.

With sea level rise, saltwater pressure upriver increases. During the 1960s drought, the salt front in the Delaware River moved from its average location at river mile 69 to mile 102. Acceptable chloride concentrations were not exceeded during any tidal cycle (Hull et al., 1986). Under assumptions of a 2.4- and 8.2-foot rise in sea level, a movement of the salt front an additional 10 miles upriver during a repeat of the drought of record could be expected. This is sufficient to increase salinity at Camden and Philadelphia intakes beyond tolerable levels during 15 percent of tidal cycles, for a 2.4-foot rise, and 50 percent of tidal cycles for a 8.2-foot rise (Hull et al., 1986). Increased salt water infiltration into the Mahogothy aquifer serving southern New Jersey also is likely, meaning increased flows in the Delaware will be required to preserve this source of supply.

Reasoning by rough analogy to the Delaware River's behavior under increased sea levels is an inherently unsatisfactory analytic technique. The geometries of the Delaware and Hudson estuaries are different now and would alter with rising sea level (Hull et al., 1986). Nevertheless, the absence of any modeling studies designed explicitly to account for sea level rise means that such an analogy is the only practical way to make projections. For estimating potential order of magnitude effects, the analogy is reasonable. (In addition, the average flows in both rivers are roughly comparable: 21,500 ft^3/sec. average flow into the Delaware estuary; 17,700 ft^3/sec. in the Hudson at Poughkeepsie (Hull et al., 1986, and Pirnie, 1986).

Currently, the maximum reach of the salt front during summer in the Hudson under normal flow conditions is at Peekskill, at river mile 45, although in a typical year, the front (chloride concentration of 50 mg/L) fluctuates from 20 to 60 miles north of the Battery (Pirnie, 1986). If the percentage change in salt front location estimated for the Delaware is applied to the Hudson -- adding 10 river miles to the 30 already experienced during drought -- the Chelsea and Poughkeepsie water intakes are rendered unuseable given current standards of drinking water taste and odor. During the drought year of 1982, the salt front fluctuated between river miles 30 and 80, with a median location roughly at river mile 55. On this basis, a 33 percent increase in the projected advance would place the salt front at river mile 58, with fluctuations between miles 33 and 87. Based on the 1982 experience, the Chelsea station would be rendered inoperative roughly 7 months out of the year, the Poughkeepsie intake 3 months. A local water supply planner estimates even a 0.8-foot rise in sea level would render the proposed Chelsea intake inoperative during droughts (Schwartz and Dillard, 1988).

An additional constraint is that salt front movement in the Delaware due to sea level rise means current New York system withdrawals from the basin would adversely impact communities in the lower Delaware, including Philadelphia. Cuts in Delaware withdrawals under a revised consent decree are likely.

If the Chelsea were unavailable during droughts, no increase in dependable yield could be credited to this potential source, thus removing 200 mgd emergency capacity from the network as currently projected. If the net basin supply behaves as estimated in the preceding section, producing an estimated loss of between 12 percent (155 mgd) and 29 percent (375 mgd) of current supply, the total loss in dependable yield could range from 355 mgd to 575 mgd. With a conservative estimate of 12 percent supply loss, and assuming that demand management efforts are as effective as now projected, the estimated supply deficit for the New York system will increase from about 361 mgd to 796 mgd, as shown in Table 7.

TABLE 7

SUMMARY OF CLIMATE EFFECTS ON SAFE YIELD

	MGD
Demand	
Projected 2030	1,651
Climate-induced additions	
Recreational and urbaculture	30
Air-conditioning	50
Total	1,731
Safe Yield	
Projected 2030	1,290
Climate-induced subtractions	
Chelsea intake	**
Basin supply	355
Total	935
Current projected deficit	361
Climate-induced deficit	796

NOTE: Projected demand of 2030 is Hazen and Sawyer's projection of 1709, net demand management savings of 158 mgd.

** Loss of temporary capacity of 200 mgd from Chelsea intake, and 50 mgd from Brooklyn groundwater not calculable as safe-yield loss.

POLICY RESPONSES TO CLIMATE EFFECTS

Despite an increasing trend in recent years toward noncapital project solutions to water supply deficits, the combined effects of climate change and sea level rise almost certainly will require capital solutions. Moreover, increasing regional scarcities will demand increased regional cooperation in water supply development and allocation, making closer linkage of water management institutions probable.

Capital Project Responses May Cost Billions

Under the scenario examined above, a possible outcome of global climate change from the standpoint of New York water supply alone is an increased supply deficit of about 435 million gallons per day, assuming current projects yield additional supplies as projected.

The additional impoundments required to address the water supply deficit projected for New Jersey and the Delaware River Basin may create enough capacity to cover at least part of this deficit. Delaware River flow augmentation studies estimate that about 100 million gallons per day of additional storage capacity will be required (Hull and Titus, 1986), roughly one-fifth of the estimated storage capacity of the Tock's Island Reservoir, once projected for development on the Delaware, or half the storage capacity available if a series of smaller projects in the region moves forward.

The ecologically undesirable Tock's Island development on the Delaware River, projected to yield 650 million gallons per day, would cost $850 million (U.S. Army Corps of Engineers, 1977). In addition to its role in Delaware River flow augmentation, a portion of the additional supply created through this development would almost certainly be used to augment system yields in northern New Jersey. The augmentation is needed to offset climate-induced supply deficits caused by increased demand and probable limits on withdrawals from the Raritan and Passaic Rivers resulting from sea level rise. Therefore, even with development of Tocks, or especially a regional network of smaller reservoirs that would deliver a smaller supply, some regionwide shortfall would remain.

Therefore, climate-induced water supply deficits in New York and the lower Hudson region probably will prompt development of a project similar to the currently proposed Hudson River flood skimming project. This project would require the development of new impoundments and transmission facilities, and would produce an estimated increase in safe yields of about 800 millions gallons per day. This solution would be expensive -- about $2.8 billion (in 1986 dollars). In the long run, it also leaves little room for additional growth. An alternative project currently in initial planning stages, the Hudson River phased flood-skimming project, would yield 1,500 million gallons per day at a projected cost of $7-14 billion (Mayor's Intergovernmental Task Force, 1987).

With New York system capital project development of this magnitude, the Delaware River Basin/northern New Jersey water supply solution likely could be scaled down to an overall development less demanding in terms of capital and political costs than would be the case with Tocks Island. This linkage points up an important institutional consequence likely to result from global climate impacts on water supply availability -- the increased need to coordinate water management responses.

Water Management Responses Will Be Controversial

Though the immediate solution to water supply deficits would be development of impoundments sufficient to ensure overall safe yield to the system, the ultimate response of water management agencies in the region may have to be creation of new water management institutions.

As indicated in the preceding discussion, water supply decisions made by any single actor in the region have important implications for other actors. The Supreme Court decision limiting New York withdrawals from the Delaware is only the most visible manifestation of this interlinkage. Under conditions of global climate change, new sources of water will have to be developed, and new competitors for regionwide water supplies will emerge. Thus, two critical issues will have to be faced. Who will plan and finance the new capital projects necessary for growth? Who will play the central role in water allocation? In other States, New Jersey a prime example, when regional water management issues become critical, the State takes the lead role in financing and management.

Localities with a traditional bias toward self-sufficiency in water supply tend to resist centralization of water management decision-making. In addition, the siting of capital projects involves clear winners and losers. For example, one prime site for an impoundment currently considered a long-range solution to the New York supply deficit would involve reservoir construction in Adirondack State Forest, a solution prohibited by New York State legislation. Increased water scarcity would doubtless alter political balances. Acrimonious fights over capital project siting are likely.

The Response Must Start Now

Although the rise in sea level is projected to occur gradually over the next 100 years, the long lead times in water project development argue for the incorporation of climate effects in water supply planning now. One early step that can be taken is to include modeling of sea level effects in upcoming work by the U.S. Geological Survey to evaluate the behavior of the saltwater front in the Hudson River. Clearly, the viability of several projected water supply solutions is keyed to the behavior of the Hudson River saltwater-freshwater interface. The additional analysis required to include sea level rise effects would not be substantial and is an important example of how incremental changes in current water supply planning practices can forestall potentially serious future adverse effects.

In addition, incremental capital project changes that have no large cost implications can be made. Recently, a routine design decision on the placement of an outfall of the Third Water Tunnel incorporated an extra margin of safety, designed to allow for sea level rise. Though no formal analysis was conducted to guide this decision, it represents the kind of planning adjustment that should be made part of the design calculus of future water planning and management decisions.

REFERENCES

American Association of State Highway and Transportation Officials, Manual for the Design of Pavement Structures, Appendix G, "Treatment of Roadbed Swelling and/or Frost Heave in Design," 1987.

Bowersock, John, Interview with The Urban Institute, March 17, 1988.

Carpenter, Samuel H., Darter, M.I., and Dempsey, G.J., and Herrin, Stan, "A Pavement Moisture-Accelerated Distress (MAD) Identification System," Volumes 1 and 2, FHWA/RD-81/079, September 1981.

Chang, F.F.M., A Statistical Summary of the Cause and Cost of Bridge Failures, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1973.

Citizens' Union Foundation of the City of New York, Thirsty City: A Plan of Action for the New York City Water Supply, 1986.

City of Cleveland, Energy Planning and Management: A Project Report, prepared for the Urban Consortium Energy Task Force, Cleveland, December 1982.

City of Miami Department of Public Works, Storm Drainage in South Florida, Miami, Florida, (n.d.).

City of Miami Department of Public Works, Storm Drainage Master Plan, Executive Summary, September 1986.

Cohen, Stewart J., "Impacts of CO_2-Induced Climate Change on Water Resources in the Great Lakes Basin," Climate Change, 1985.

Department of County Engineer of the County of Los Angeles and Engineering Science, Inc., Development of Construction and Use Criteria for Sanitary Landfills, Report PB-218-672, U.S. Environmental Protection Agency, 1973.

Diamond, Craig, Senior Research Associate, Florida Atlantic University-Florida International University Joint Center for Environmental and Urban Problems, Interview with The Urban Institute, September 1988.

Downtown Development Authority of the City of Miami, Florida, Consolidated Application for Development Approval for Downtown Miami as Development of Regional Impact, Miami, Florida, February 1988.

Energy Information Administration, Annual Outlook for U.S. Electric Power, 1987, Department of Energy, 1987.

Federal Highway Administration "Section 137 Studies: Climate and Apportionment and Interstate 4R Apportionment, prepared for the United States Congress, December 1983.

Fulkerson, R., Chairman, Technical and Performance Committee, Cooling Tower Institute, personal interview with The Urban Institute, June 1988.

Getz, Robert, "Interview with The Urban Institute," March 16, 1988.

Gurwitz, Aaron S., and Kingsley, G. Thomas, The Cleveland Metropolitan Economy, prepared for the Cleveland Foundation, Rand Corporation, March 1982.

Hazen and Sawyer, P.C., Delaware-Lower Hudson Regional Water Resources Management Strategy, New York State Department of Environmental Conservation, September 1987.

Heath, Ralph C., Basic Ground-Water Hydrology, U.S. Geological Survey Water Supply Paper 2220, U.S. Government Printing Office, 1987.

Hirsch, J., "As Streets Melt, Cars Are Flummoxed by Hummocks," The New York Times 137 (47599). August 16, 1988, pp. B1, B5.

Hull, C.H.J. and Titus, J.G. Greenhouse Effect, Sea Level Rise, and Salinity in the Delaware Estuary, Washington, DC: U.S. Environmental Protection Agency, Delaware River Basin Commission, May 1986.

Jenne, Roy, "GISS and GFDL Climate Projections: National Center for Atmospheric Research, 1988.

Linder, K.P., M.J. Gibbs, and M.R. Inglis, "Potential Impacts of Climate Change on Electric Utilities", Albany, NY: New York State Energy Research and Development Authority, Report 88-2, December, 1987.

Mayor's Intergovernmental Task Force on New York City Water Supply Needs, Managing for the Present, Planning for the Future, December 1987.

Metro Dade County Florida, Comprehensive Development Master Plan, April 1988.

Metropolitan Dade County Planning Department, Comprehensive Master Plan for Dade County, Florida, Miami, Florida, July 1979.

Morgan, W. Douglas, and Smollen, Jonathan C., "Climate Indicators in the Estimation of Municipal Water Demand," Water Resources Bulletin, 12:3, 1976, pp. 511-515.

Norman, J., American Society of Heating, Refrigerating, and Air-Conditioning Engineers, personal interview with The Urban Institute, June, 1988.

Parham, David, Infrastructure Condition and Financial Monitoring Data Base Report, Urban Institute Report submitted to the Greater Cleveland Growth Association, September 1985.

Peterson, George E., Miller, M.J., Godwin, S.R., and Shapiro, C., Guide to Benchmarks of Urban Capital Condition, Urban Institute Press, 1981.

Pirnie, Malcolm, Drought Operation of the Hudson River Pumping Plant Located at Chelsea, Dutchess County, New York, Draft Environmental Impact Statement, November 1986.

Post, Buckley, Schub and Jerrigan, Inc. and Department of Army, Corps of Engineers, Lower Southeast Florida Hurricane Evacuation Study, prepared for Monroe, Dade and Palm Beach Counties, June 1983.

Quinn, Frank H. (1987), "Likely Effects of Climate Changes on Water Levels in the Great Lakes, in Preparing for Climate Change, Proceedings of the First North American Conference on Preparing for Climate change: A Cooperative Approach, Washington, D.C., October 1987.

Raoul, Joseph and Zane M. Goodwin (1987), "Climatic Changes - Impacts on Great Lakes Levels and Navigation," in Preparing for Climate Change, Proceedings of the First North American Conference on Preparing for Climate Change: A Cooperative Approach, Washington, D.C., October 1987.

Rhoads, P.B., Shih, C.C. and Hamrick, R.L., "Water Resource Planning Concerns and Changing Climate: A South Florida Perspective," in Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues, conducted by the Science and Public Policy Program, University of Oklahoma and sponsored by the U.S. Environmental Protection Agency, 1987.

Rind, D., and Lebedeff, S., "Potential Climate Impacts of Increasing Atmospheric CO2 with Emphasis on Water Availability and Hydrology in the United States," NASA Goddard Space Flight Center Institute for Space Studies April, 1984.

Rind, D., Goldberg, R., and Ruedy, R., "Change in Climate Variability in the Century", Goddard Space Flight Center Institute for Space Studies, unpublished draft, 1988.

Schwarz, Harr E., and Lee Dillard, "Chapter III-D Urban Water," in AAAS Global Climate Change Report, Washington, D.C., 1988.

Shih, George, "Everglades National Park and the Rising Sea Level," Memorandum, South Florida Water Management District, January 9, 1984.

South Florida Water Management District, Water Resources Data and Related Technical Information to Assist Local Government Planning in Dade County, West Palm Beach, Florida 1987.

State of New Jersey, Department of Environmental Protection, Division of Water Resources, The New Jersey Statewide Water Supply Master Plan, Draft Update, August 1987.

Temple, Barker & Sloane, Inc., "Survey of Operating and Financial Characteristics of Community Water Systems", Office of Drinking Water, U.S. Environmental Protection Agency, October, 1982.

Tripp, R., Communication to the Urban Institute from Howard, Needles, Tammen and Bergendoff, 1988.

U.S. Army Corps of Engineers, North Atlantic Division, Northeastern United States Water Supply Study, Summary Report, July 1977.

U.S. Department of Commerce, Bureau of the Census, County and City Data Book, 1983.

U.S. Geological Survey, Resource-Management Evaluation and Study of Salt-Water Movement Within the Transition Zone of the Hudson River Estuary, New York, 1988.

Vermani, Y.P., Clear,, K.C., and Pasko, T.J., Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, FHWA/RD-83/012, September 1983.

Walker, J. Christopher, and Friedman, Mark A., "The Greater Cleveland Community Capital Investment Strategy: Five Years Later," Project Report prepared for the Greater Cleveland Growth Association, March 16, 1988.

IMPACTS OF EXTREMES IN LAKE MICHIGAN LEVELS ALONG ILLINOIS SHORELINE: LOW LEVELS

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FINDINGS[1]

The 9-month investigation studied the effects and adjustments from the record low levels of Lake Michigan during 1964-1965. The focus was on the effects along the 101-km shoreline of Illinois. The expectation was that this case study would provide a basis for estimating future effects of altered lake levels due to future climate change, and that the results would be potentially transferable to other similar urban shoreline areas of the Great Lakes.

The data collection effort revealed that locating quantified data on the impacts of the low lake levels in the early 1960s was very difficult. Many original institutional records were destroyed or lost, and a newspaper content analysis was of marginal value. Hence, it was impossible to do an in-depth quantified analysis of the direct, secondary, and tertiary impacts. We depended on structured interviews with local experts in various public and private sector positions to provide much information on the impacts and responses of the 1964-65 low levels, and in turn to assist us in assessing future impacts of extreme climate change. We believe the analysis was sufficient to detect the impacts of significance and to develop useful qualitative assessments of these. As in any study attempting to estimate future socioeconomic and physical effects from extreme climate conditions never before sampled, the estimated impacts and responses must be considered speculative.

Analysis of the physical factors affecting low-water conditions revealed that the record low-level period of 1964-65 would have been worse if precipitation over Lake Superior had been below average (it was near normal). A series of climate scenarios based on (1) three global climate model estimates from doubling of CO_2 with atmosphere, and (2) on extreme annual precipitation values of the last 134 years on the Great Lakes Basin, were used to derive estimates of potential low lake levels in future years. These provided a variety of estimates of lake level lowerings ranging from 0.4 to 2.5 meters, and were used for estimating future impacts. The interannual variability of lake levels in low-level (dry) periods was studied and found to be slightly greater than in extremely wet periods. This would be an important factor needed for estimating future effects of low levels. The climate scenarios did not provide estimates of interannual variability or of long-term fluctuations apt to occur.

An important concept about the effects of low (or high) lake levels is the fact that neither extreme is desirable. In low lake level periods, detrimental shoreline effects are minimized, relevant to those in high levels, but during low level periods, considerable economic loss is experienced by shipping and power generation interests across the basin. In general, the reverse situation occurs during high lake level periods.

Analysis of the effects of low lake levels during 1964-1965 along the Illinois shoreline of Lake Michigan revealed seven areas of impact. Effects on shorelines were mixed, and in general, local shipping was hurt. Effects on recreation were mixed, and in general, industry and most commerce were hurt. Problems developed in the water management and water supply areas, along with problems in land use management that evolved during and after the low water period. Some institutional impacts were positive, but in general, the effects led to adjustments that were costly to local, state, and federal government entities.

The two major impacts discerned, damage to shoreline structures and encroachment of structures closer to the lake, developed during the 1964-1965 low levels, but both also required a sequence of low and then high water levels. The City of Chicago frontage repairs relating partly to the low-water-induced dry rot to wooden structures and subsequent high water wave action may cause up to $800 million to repair. Damage to buildings and houses built too close to the lake during the low water periods has been excessive with many damaged and a few destroyed.

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[1] Although the information in this report has been funded partly by the U.S. Environmental Protection Agency under contract CR-814658-01-0, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

In summary, the low lake levels of the 1960s did not provide many major economic impacts or require adjustments at the time of their occurrence. The economic effects were mixed, some gains and some losses. The low-water period was too short to lead to many adjustments. An important finding about impacts was the "low-high problem." Impacts of future lower lake levels, when the climate changes occur to produce these, will depend extensively upon the degree of long-term oscillations (decadal) in levels that occur with the lower lake levels.

The second major part of the "low lake study" concerned what may occur in the next 30 to 70 years as the Illinois area and the basin experience a drier and warmer climate than any of the past 200 years. We had planned to estimate the future impacts, responses, and policy actions largely on the data/findings of the record low-water period of the 1960s. However, the data were poorer than we hoped and we learned that the low period was too short to cause many impacts or adjustments. Hence, our futuristic estimation had to be more speculative than desired. Each climate scenario involving a different lowering of Lake Michigan was studied.

The economic impacts of future lake levels projected to be reduced from current averages by 0.5 to 1.0 meter during the next 50 years were not seen as too severe. It appears these can be adjusted largely by normal maintenance and replacement costs to affected facilities. Illinois shoreline impacts will probably cost $100 million. However, the lake levels will be sufficiently low and the water quality decreased to make meeting water demands very difficult and controversial. A more arid climate will mean less water to serve Illinois areas beyond the basin with attendant problems in meeting needs of the Illinois and Chicago River and canal systems, as well as for public and industrial water requirements upped by population growth and a warmer-drier climate. Increased diversion of lake waters will be sought but resisted by national and international interests; this will lead to increased use of groundwater, already a partly depleted resource in the region. Impacts to the environment will include loss of the Illinois wetlands and habitats if the lake falls too rapidly and degradation of the quality of lake water and groundwater in aquifers affected by the lake. Increased water temperatures will make cooling more difficult, and shipping of Illinois goods will become more expensive. The net effect is extremely detrimental to the economy of Illinois and to the future of the Chicago Metropolitan Region. The related policy implications are considered to be major.

If the average lake level falls farther to 1.25 or 2.5 meters, even more sizable economic impacts will occur, costing an estimated $280 million and $540 million, respectively. Parts of these costs could be ameliorated within normal replacement costs, particularly if a master plan for changing affected facilities is developed and implemented. The degree of climate change and ensuing lake level greatly affect the seriousness of the economic outcome, but the environmental and water resource effects are extremely serious in all three climate scenarios. Development and use of a master plan for the Illinois area (and Great Lakes), possibly under the program of planning called for in the 1985 Great Lakes Charter, would be one important activity to launch now.

More specification about the nature of the climate-lake change (rate of lowering, total amount of lowering, and variation around the new mean) is needed. Variations of levels of 3:1 from the models reveal sufficient uncertainty to make management actions based on any one of them difficult, yet some can begin.

It would appear, given current problems with transboundary issues on the basin, that major policy issues will be created at the community scale up through the state, regional, national, and international levels. New approaches and institutions to deal with the scope and magnitude of the problems will be necessary.

Certain research recommendations appear. Clearly, the GCMs must be more thoroughly developed to achieve greater regional specificity and uniformity in their projected outcomes. Pressures will develop for increasing lake water supplies in prolonged low-level periods. This will call for research on subjects such as climate prediction, weather modification, and evaporation suppression. We lack sufficient information on how climate change affects our physical systems and economy; hence applied research in these areas is needed. Studies of policy options and institutions to address the problems and to manage the jointly shared resource of the Great Lakes also are in order.

CHAPTER 1

INTRODUCTION

GOALS AND OBJECTIVES

This document reports on a limited (8-month) study of the physical and socioeconomic effects and responses along the Illinois portion of the Lake Michigan shoreline resulting from extremely low levels of Lake Michigan that occurred in past years (1963-1965), plus speculations about effects and responses that may occur with lower lake levels due to future climate change.

The project had three objectives. The primary objective was to provide a measure of the types of physical and socioeconomic effects resulting from recent record low lake levels. The second objective has been to measure and assess the adjustments that the private and public sectors in Illinois have made as a result of these extremes. The third objective was to provide speculations about the effects and adjustments relating to future low lake levels due to a warmer and drier climate.

Central Concept of the Study

The first important concept is that a short-term (8-month) study of the effects of low lake levels on shorelines and the related socioeconomic impacts and responses using the 101-km Illinois shore was useful for two reasons. The Illinois shoreline (largely Chicago and suburbs) samples the variety of lake frontages typically found in all metropolitan areas (harbors, intakes and outlets, diversion lockages, beaches, shore protection structures, parks, urban buildings, and residences). However, the shoreline did not sample agricultural frontages and had only minimal natural environmental frontage (limited wetlands). Second, such an investigation by a state agency and university with easy access to institutional historical records and key individuals allowed for a meaningful analysis **in a short time period** if the project's scope was not too broad.

The second important concept of this study relates to its scope. The time limitations meant it had to be confined to the dimensions of the physical impacts and socioeconomic impacts and responses along the Illinois shoreline. This was not a study of the effects of low lake levels on Lake Michigan including the quality of its waters, shipping, or hydroelectric power generation on the Great Lakes, or of environmental impacts beyond those identifiable **along the Illinois shore**. The issue of altered water quality in the lakes is a central question related to a major change in climate leading to lower water supplies in the basin. However, analysis of this major issue was **beyond the scope** of this study. The U.S. EPA did not provide to this study estimates (as they did for changed lake levels) of the potential changes in water quality; thus, we did not address this issue in any substantial way.

The third central concept is that the study was designed: (1) to investigate the impacts and responses to the record low lake levels during the 1960s, and (2) to use these as a basis for estimating future impacts and desired policy actions from presumed climate changes. This approach was considered meaningful because the low level period was sufficiently recent to have sampled socioeconomic conditions generally representative of present and near-future conditions. Hence, findings were to have been transferable for consideration of future effects to metropolitan areas of lower lake levels resulting from a warmer and drier climate.

Two Discoveries Affecting the Study and Its Findings

As the data collection and analysis progressed, we found two limitations that greatly altered the study's design, analytical approach, and findings.

The first major limitation encountered related to the **data on effects and responses** during the low lake levels of 1963-65. We were unable to locate many of the expected records of actions relating to low levels during

1963-65 in the files of the City of Chicago, state agencies, or federal agencies. Most records of that period had been lost or destroyed during the past 25 years. Our investigation of newspaper records revealed little useful information. Thus our major remaining source of information was that to be secured from decisionmakers who held positions in key public and private sectors during the 1960s. We designed the data collection around a structured interview approach. Through this process we learned that: (1) the impacts and responses **during** 1963-65 were largely negligible, but (2) that major impacts related to the low levels occurred when lake levels achieved record high levels in the 1970s and 1980s.

Second, the analysis of effects of the record low lake levels (which were limited to 1963-65 and followed by a rapid increase in levels) further revealed that the low period was too short to have caused many major impacts and few responses. (The only major effects of the low levels occurred from the damages ultimately created when lake levels subsequently reached record high levels in the 1970s and 1980s.) The lack of utility of the 1963-65 sampling period forced a shift from the planned approach (based on calculating future effects of **prolonged** low levels using the 1963-65 results), to an approach that was more speculative than data based. Further, two of the three climate models that were used to estimate future lake levels generated levels much lower than those experienced in 1963-65, further requiring speculation about future effects and responses. This situation led to a second round of structured interviews using questions based on **suspected** impacts. From the responses, estimations were made of potential impacts including their costs, and speculations were made about institutional/policy responses to deal with the impacts.

This report describes methods used in acquiring data and developing climate scenarios in Chapter 2; the results available appear in Chapter 3; and the interpretation and significance of these results are addressed in Chapters 4, 5, and 6.

CHAPTER 2

METHODOLOGY

MEASUREMENT OF EFFECTS AND ADJUSTMENTS TO RECORD LOW LAKE LEVELS

This study focused on an intensive investigation of the record low lake levels occurring on Lake Michigan during 1964-1965 for two reasons. First, the projected, most likely climate change in the Great Lakes Basin from global models is for drier and warmer conditions. This would normally lead to lower lake levels. Second, time does not permit a thorough effects analysis of both record high and record low conditions. Further, the effects of record high levels have been documented in recent publications (Changnon, 1987).

Data Sources

Data collection for the effects and adjustments from the record low lake levels during 1963-1965 included five areas of activity. These included telephone interviews and discussions with individuals who played key roles in affected organizations during the low-levels period. Second, it involved visits and structured interviews with certain experts to gather data. A third means of data collection involved searches of records of public agencies affected by the record low lake levels. A review of newspaper contents during this low lake level period was used as a fourth data source. Finally, aerial photographs of the shoreline were obtained during low and high level periods.

Climate Scenarios

It was recognized as the project began that several of the impact studies under the broad charge of the EPA Climate Change Program were attempting to quantify, through use of various global climate models (GCMs), the effects of a very severe climate change due to large increases of CO_2 (and other trace gases) in the atmosphere. These models have been based on assumptions from data gathered during a regime of climate much less severe than that being projected in the models. This brings decided uncertainties, as do any estimates of possible extreme future conditions. Three GCMs were used, and they projected varying climate conditions for the Great Lakes Basin. When these were used in lake level models, they led to projections of lowering of Lake Michigan by 0.86 m, 1.25 m, and 2.5 m.

For this study and as part of the international analysis of lake level problems under the U.S.-Canada Reference of 1986, record-based future climate scenarios were also seen as valuable for equating the impacts from the 1963-1965 low levels to those that may occur with more severe future dry conditions (seen as likely as the GCM projections due to doubling of the atmospheric content of CO_2).

For these reasons, this project helped develop "climate scenarios" as estimates of likely extreme periods of low levels on Lake Michigan (and the other Great Lakes since their levels are interactive). These, along with the $2xCO_2$ values in the GCMs were used with lake level models to calculate future levels of Lake Michigan and other lakes. These help serve the purpose of speculating on the future impacts of low levels by having four estimates on likely low levels that could be experienced. Paleoclimatic research by Larsen (1985) suggests that extremes greater than those sampled in recent years have occurred due to climatic factors at several times during the past 2,500 years (see Figure 2). It is not certain whether future extremes produced by natural causes will be matched or exceeded by the projected climate changes due to man's influence on the atmosphere. Given these uncertainties, we concluded that it was reasonable to investigate the effects of the record low lake levels during the 1960s along the Illinois shoreline. From the types of impacts noted, we hoped to make informed estimates of the types of effects and adjustments apt to result from future lake levels that might be greater than experienced in the 1960s.

Development Process. Climate scenarios, defined as descriptions of possible climate conditions at some unspecified future time, can be developed by various processes. These include those generated from empirical analysis, stochastic analysis, and by the physically based global climate models. Climate scenarios are not predictions but serve as plausible examples.

It was decided to develop a set of scenarios for describing possible future climate conditions in the Great Lakes Basin. These were based on use of historical climate conditions to form climate scenarios.

The development of "climate scenarios," based on use and interpretation of historical climatic data for the Great Lakes Basin, was based on several important facts for describing, understanding, and using these analog scenarios of future conditions. We believe these are physically possible for the Great Lakes Basin.

The following conditions relate to the climate scenarios selected.

1. Are not predictions of climate based on occurrence at any specific future time.

2. Have no probability for occurrence, and are not based on any frequency assumptions.

3. Are done with the recognition that the levels of the Great Lakes have ranged above and below those sampled over the past 120 years of usable climatic record.

4. Were developed to produce precipitation and temperature values needed as input for hydrologic models of the Great Lakes so as to generate lake levels and net basin supply (NBS) values.

5. Would be constructed from the climatic extremes sampled over the past 133 years (that is, "instrument-based" values).

6. Would represent a "snapshot" of conditions in a period that could occur, without knowing the likelihood or time of occurrence).

7. Would be constructed from extremes in annual precipitation data. The annual values from about 1854 to 1986, and their aberrations around the average, would be used to define "extreme years."
   Temperature values with these selected years would be used.

From these "boundary conditions," climate scenario models were chosen to reveal one possible dry period. It was to be based on measured historical data from the Great Lakes Basin. It was decided that these analog-type scenarios would be 12-year periods of time, or composite climatic blocks (Wigley et al., 1986). A 12-year period was chosen, based largely on known response times in the climate-hydrologic models for the Great Lakes to reach equilibrium. It is also supported by harmonic-spectral analyses of midwestern historical precipitation data indicating, at varying levels of statistical significance, wavelengths of 10 to 13 years in length (Neill and Hsu, 1981).

These climate scenarios provide values for input to existing hydrologic models so as to determine net basin supply (NBS) values for ultimate use in hydrologic models of the Great Lakes Basin so as to project levels of Lake Michigan (and the other lakes). Since precipitation is a primary factor in determining NBS and the lake levels, it was decided to develop the climate scenarios solely around precipitation conditions. As will be described in the following text on scenario development, annual precipitation values for 1854-1986 were used in selecting the scenario periods, and then actual monthly precipitation values from the selected years were used as the input to the hydrologic models needed to obtain the NBS values.

Periods to be selected to portray extremely dry periods with a 12-year duration first had to contain (or exceed) a given number of below-average years. A dry period for consideration would contain 8 or more years with below-average precipitation to qualify for the dry period analysis. This criterion was based upon the fact that the frequency of below-average annual precipitation events has been shown to be the most critical factor in NBS (Quinn, 1986) and lake levels (Changnon, 1987).

The next aspect considered was the selection of the temperature data. Temperature values were not chosen separately. The precipitation-temperature relationships found in the actual historical data were retained. Actual daily and monthly data on temperatures (and humidities, winds, and evaporation) were utilized from the historical records for the years selected on the basis of their precipitation extremes. For years prior to the availability of daily data (as needed in the scenarios for the hydrologic model), algorithms relating the precipitation values to temperature and other daily conditions from the 1948-1985 period were used.

The most extreme dry periods extending across the Great Lakes Basin were selected. This was done by screening the historical annual precipitation values of each Great Lake Basin (1854-1986) and then selecting the ones extending across the entire Great Lakes Basin.

This initial screening identified all candidate 12-year periods based on the presence of 8 or more years with below (dry) the average precipitation. The net departure of the total precipitation in each candidate period was also determined, yielding negative values for the candidate dry periods.

Once the candidate periods and their two measurements of severity (the number of extreme years in the 12 and the total precipitation departure) were completed for each lake's basin, these periods were intercompared between basins. Those found to be common, or present on all four basins, were the final candidates for the actual period scenarios for the Great Lakes Basin. They are listed in Table 1.

Each period on each lake basin was ranked, as shown, based on the magnitude of the 12-year cumulative precipitation departure. For example, in the Lake Superior Basin, the 1914-1925 value of -9242 mm (Table 1) was the highest ranked dry value. The four basin ranks thus achieved for each candidate 12-year period shown in Table 1 were summed to obtain a "basin-wide rank score." As shown in Table 1, this score for 1914-1925 was 7, the lowest of the six candidate dry periods. Hence, it was selected to represent the driest 12-year period in the Great Lakes Basin.

The desired analog climate scenario was developed from 1914 to 1925. This period was modified according to the following criteria:

1) The arrays of dry years were retained in the sequence they occurred across the entire Great Lakes Basin, as based on the sum of the annual departures of each lake basin.

2) The magnitudes of the annual precipitation values were changed if they were negative in the dry periods. These changes were done for the basinwide annual values (not for each basin).

3) In the 1914-25 dry period chosen, the 8 or more dry years (out of 12) were magnified by substituting the 8 (or more) driest annual values in 1854-1986.

4) The nondry years in the 12-year dry period would not be altered.

5) The process of substitution of more extreme values began with the ranking of the basinwide mean departures for each year in the 12-year periods, as shown in Table 2. For example, the 1914 basinwide value was -3992 mm and it ranked as the fourth largest of the 12 values during 1914-25 (1923 with -5668 mm was top ranked, see Table 1).

Table 1. 12-Year Dry Periods Common to All Great Lakes[1]

Period	Superior			Michigan-Huron			Erie			Ontario			Rank score
	No. dry years	Cumulative departure, mm	Rank	No. dry years	Cumulative departure, mm	Rank	No. dry years	Cumulative departure, mm	Rank	No. dry years	Cumulative departure, mm	Rank	
1910-21	9	7503	4	8	2104	6	8	5191	4	9	6130	4	18
1913-24	9	8270	3	8	2646	5	8	4042	5	9	6019	5	18
1914-25	10	9242	1	9	5944	2	9	5834	2	10	7092	2	7
1915-26	10	8992	2	9	5856	3	9	5402	3	10	6162	3	11
1916-27	10	6331	5	8	3774	4	8	3949	6	9	4282	6	21
1930-41	7[2]	1001	6	10	9287	1	8	6107	1	10	7513	1	9

[1] Based on 8 or more years with annual precipitation below average for 1854-1987.

[2] Included because of severity in all other basins.

Table 2. Climate Scenario Values for an Extremely Dry 12-Year Period

Rank	Year	Basin-wide Departure, mm
1	1931	-8004
2	1934	-5760
3	1923	-5668
4	1936	-4890
5	1925	-4502
6	1918	-4426
7	1963	-4303
8	1909	-4072
9	1910	-4062
10	1914	-3992
11	1915	-3959
12	1941	-3810

Year	Basin-wide Departure, mm	Rank	Substitute	Superior	Michigan-Huron	Erie	Ontario
1914	-3992	4	1936	-618	-1394	-1788	-1090
915	-3959	5	1925	-851	-1395	-1793	-463
916	3064	-	1916	824	416	846	978
1917	-1196	10	1914	-1047	-1090	-733	-1122
1918	-4426	3	1923	-1463	-1063	-1370	-1772
1919	-1300	9	1910	-1400	-1210	-439	-1013
1920	-2527	7	1963	-687	-1164	-1430	-1022
1921	-2911	6	1918	-1269	-1169	-1252	-736
1922	1181	-	1922	-169	1217	175	-42
1923	-5668	1	1931	-1346	-2448	-2141	-2069
1924	-1876	8	1909	-1550	-890	-377	-1255
1925	-4502	2	1934	-411	-1675	-2430	-1244

6) Annual values (departures) for the Great Lakes Basin for 1854-1987 were used to select the 12 largest negative (dry) years. Each of the 12 values was ranked, as shown in Table 2. The greatest 1-year value was -8004 mm in 1931 (rank 1), and the fourth highest ranked value was -4890 mm in 1936.

7) These 12 ranked values for dry (negative departures) were matched with the ranks in the actual years of each 12-year period (as described in number 4 above). Then, the substitution of values (and years) was done according to matching of the ranks. For example, in the Great Lakes Basin, the mean precipitation departure in 1914 was -3992 mm and it ranked fourth among the 12 values in the 1914-25 period. The year with the fourth greatest departure during 1954-86 was 1936 with -4890 mm. Hence, 1936 became the "substitute" year for 1914 (both ranked as fourth).

8) Once these annual substitutions were identified for each year (except for the 2 wet years in 1914-25, the actual precipitation values in each lake basin for the substitute years were those used in determining lake levels (see these values in Table 2).

9) The "climate scenario" selected out of the past had, as initial conditions, those that actually preceded it (1910-13). These established the NBS when the two periods began.

By this process, annual extremes were used to increase the departures that had been experienced in the actual driest 12-year period in recorded history (1854-1987). A climate scenario was developed based on historical values. The adjusted values are considered realistic to help define potential extreme dry periods. It was designed to retain the mix of dry years that occurred (and are possible) in the extremely driest period, but with a magnification of the annual values. This approach allowed for interannual variability during such extreme events as well as persistence of conditions during extreme dry periods. The underlying physical assumption is that the atmospheric conditions producing the extremely dry years (moved to the selected 12-year sequence) were possible for this period. That is, temporal transposition of more extreme events is within physical reason.

The extreme 12-year dry scenario was used with the GLERL hydrologic models of the Great Lakes to calculate lake levels under current conditions. These calculations projected a lowering of Lake Michigan of 0.4 meter below the 1951-80 average.

CHAPTER 3

RESULTS

IMPACTS OF LOW LAKE LEVELS

Data Sources

Each of the five sources of data relating to the effects and adjustments resulting from the record low lake levels during 1963-65 provided interesting information. The newspaper content analysis (described in the Appendix with the results presented later in Chapter 3) revealed that few of the impacts denoted from other data sources found their way into local newspaper reports of the 1964-65 era. Results suggest that a "newspaper content analysis" of effects of record low lake levels is not a suitable means of collecting extensive data on effects, or that the effects were marginal.

A second finding about data sources related to records in public and private agencies. Most private, state, and federal agencies that were impacted by the activities of the early 1960s have since lost or destroyed the detailed records of activities and financial expenditures that are necessary to develop detailed measurements on effects. Furthermore, current individuals responsible for corporate or institutional records were generally disinterested and/or unwilling to locate such records if they exist. This avenue of investigation was greatly hindered by the unavailability of many activity/financial records for assessment.

A primary means for gathering data on the effects and adjustments on the record low lake levels came through interactions with individuals who had been in responsible positions with private and public organizations during the time (1963-1965) of the low lake levels. Interactions with these individuals was complicated by the fact that most had retired and moved away from the Chicago area during the past 25 years. Extensive telephoning and letter writing was necessary to locate key individuals in the public and private sectors for these interactions. The interactions typically consisted of extensive telephone interviews (interview format is described in the Appendix). The interview process was greatly aided by the fact that most individuals contacted were aware of the scientific surveys in Illinois, and most were thus willing to take time to cooperate. These semi-structured interviews typically consisted of an hour or two of telephone conversation with each individual. In certain instances where individuals had extensive data and information, and with whom extensive telephone interviews were impractical, visits were made. Four trips were made to the Chicago area to interview such individuals; 19 individuals were extensively interviewed. Those interviewed came from the private sector (shipping, harbor and dockage construction and maintenance, and consulting engineering), and from the local, state, and federal agencies (experts in park/beaches, water management, water quality, regional planning, environmental sciences, water policy, harbor and canal maintenance, and water supplies).

Since the 1963-65 data on impacts and responses were so limited, we had to estimate future issues. In this instance, a list of potential future problems/issues from a drier climate (and lower lake levels) was developed. Several of those interviewed about 1963-65 conditions were interviewed a second time with this list of future problems. Views about these were gathered, additional issues identified, and cost estimates for addressing problems were gathered in the areas of expertise of the person interviewed.

The Illinois State Geological Survey has had a program of studying lake shore erosion and geology for many years. Their historical files, publications (Larsen, 1985), and aerial photograph library were invaluable sources of useful information. A recent inventory of lake-related research (Holms, 1987) was also of use.

The Physical Setting: Climate and Other Factors Relevant to Lake-Level Extremes

Assessment of the effects of extremely low lake levels on the Illinois shoreline and related human activities had to be based on a clear understanding of those factors that help create the extremely low levels. Furthermore, since this analysis was also to speculate about effects of future low lake levels, and those possibly lower than the historical record has experienced, it became important to consider and investigate, to some extent, the physical factors affecting lake levels, the past behavior of lake levels, and potential future climate conditions that might create extremely low conditions.

Climate Influences on Levels of Lake Michigan. There are three categories of water level fluctuations on Lake Michigan, each caused by weather and climatic fluctuations. These include short period fluctuations (hours to days), seasonal fluctuations, and longer-term fluctuations (multiple year). These are of particular concern in this overall study of low levels.

The short-period fluctuations are caused by weather disturbances. Differences in atmospheric pressure and winds over the surface of Lake Michigan can create temporary imbalances in the water levels at various locations with the resulting seiche wherein water literally piles up on one side of the lakes. These types of fluctuations are superimposed on the more rhythmic seasonal fluctuations and the less rhythmic long-term fluctuations of lake levels.

The seasonal fluctuations of the levels of Lake Michigan result from the annual hydroclimatic cycle. This cycle is characterized by higher supplies (greater precipitation) during the spring and early summer, and lower supplies during the remainder of the year (lesser precipitation and higher evaporation). The magnitude of the seasonal fluctuation is relatively small, averaging about 30 cm (1 foot) on Lake Michigan. The seasonal fluctuation is about 1/4 of the long-term fluctuations, and are superimposed on the long-term fluctuations.

The longer-term fluctuations, which are of greatest concern in this study, are the results of persistent low or high precipitation conditions within the basin that can culminate in extremely low levels, such as those recorded in 1964-65, or in extremely high levels such as recorded in 1972-73, and again in 1984-86 (Changnon, 1987). Figure 1 presents graphs based on the levels of Lake Michigan from 1860 through 1987. The annual values (Figure 1a) reveal many "sawtooth"-type variations, and one notes the extremely low values obtained in the early 1920s, 1930s, and early 1960s. Figure 1b presents the moving average of annual lake values based on 11-year periods, again showing the general low values in the 1920s and 1930s; the low values again in the early 1960s; and interdispersed higher levels. Statistical analysis of these fluctuations did not reveal any regular, predictable cycles in lake levels or in precipitation. The intervals between the periods of extremely high and low levels, and the length of such periods, vary widely and erratically over a number of years.

The maximum recorded range of levels from the extreme high to the extreme low is approximately 1.5 meters on Lake Michigan. Importantly, the timing of record annual lows (Figure 1a) in the 1960s was followed within 10 years by record high levels. It should be noted that the data prior to 1900 are suspect for comparison to later years because of connecting channel changes to the other lakes done in the 19th century. These effectively lowered the level of the lake by about 20 cm.

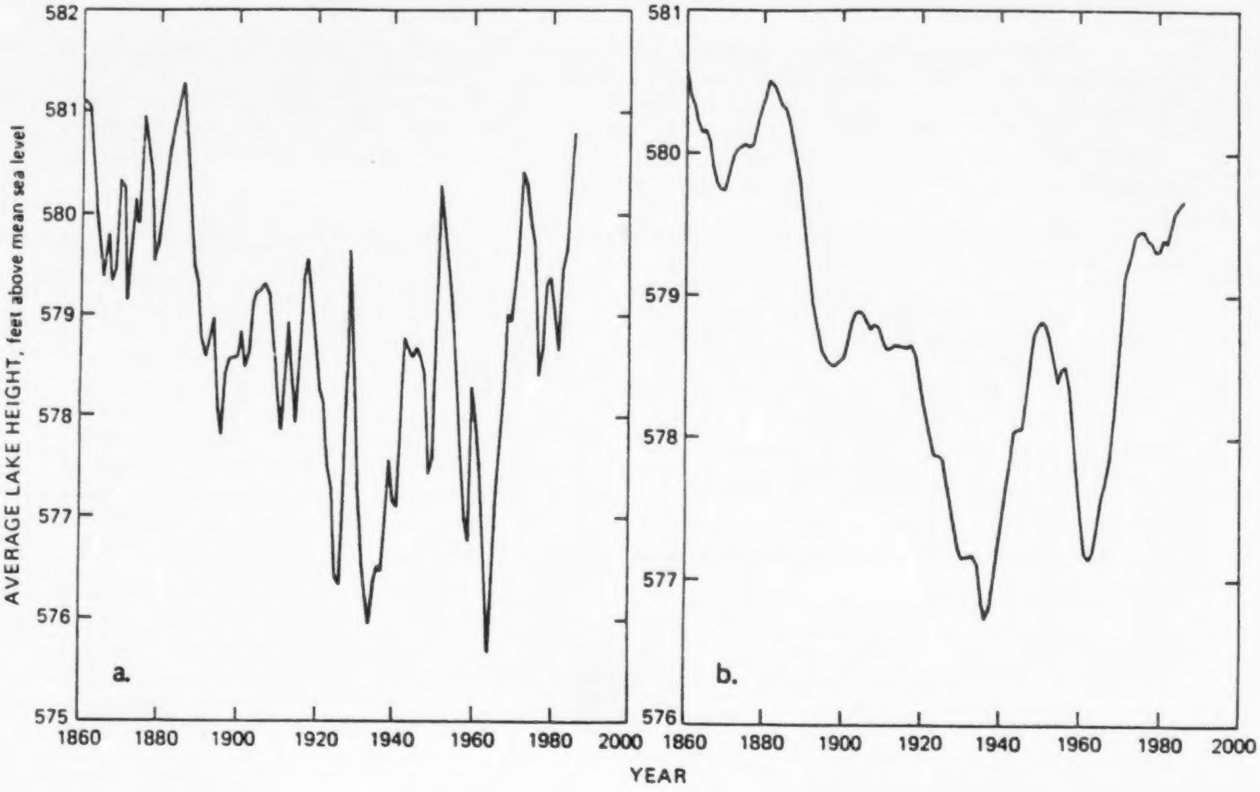

Figure 1.Lake Michigan levels (1860-1986) based on annual averages and 11-year moving averages.

Of considerable concern then to the analysis of the extreme low levels and high levels of Lake Michigan (or any Great Lake) is the tendency of the climate. Inspection of Figure 1 reveals that there have been major fluctuations in the climate over the last 120 years. Examination of the values of Figure 1b for the period of about 1900 to present (that period unaffected by the changes in lake levels mentioned above) shows a period of generally increasing levels since 1940. This is substantiated by a recent analysis of precipitation on the Lake Michigan Basin from 1896 to 1985 (Changnon, 1987), suggesting an increasing precipitation regime over the last 50 years. There is a suggestion that the current climatic regime is a part of a period moving towards ever wetter conditions which also includes increased cloudiness and reduced over lake evaporation.

Another feature of the climate conditions, particularly of recent years, is the high frequency of extreme events, suggesting a shift to greater climatic variability. Comparison of the annual values (Figure 1a) for 1900 through 1940, as compared to those from 1941 to 1985, reveals the earlier period had fluctuations but not as large as those in the last 45 years. This is reflected in high levels in the 1950s, early 1970s, and mid-1980s intermixed with the record lows in the 1960's. As will be shown in the effects analysis, such fluctuations in climate are as important as the general trend to wetter or drier conditions.

Other Factors Influencing Levels of Lake Michigan. The vast surface areas of the Great Lakes, which are equal to nearly half the land areas that contribute runoff to them, constitute an important factor in their water levels. Small differences in lake levels represent enormous quantities of water. Both the seasonal and long-term level fluctuations in lake levels are the result of changes in lake volume. The variation in the supply of water, which is primarily the difference between the precipitation on the lakes and their basins, and the evaporation from them, is the primary cause of the seasonal and long-term fluctuations. Net monthly water supplies to the Lake Michigan Basin, for example, range from a maximum of 594,000 cubic feet/second-months to a minimum of -86,000 cfs-months. The negative value indicates that losses from evaporation and outflow exceed the supply from precipitation and inflow (runoff) to Lake Michigan. However, large variations in supplies to the lake are absorbed and modulated to such an extent that its outflow is remarkably steady. Because of the large size of the Lake Michigan (and the other lakes), and the very limited natural discharge capacities of the outflow rivers from them, extremely high or low levels (and flows) persist for some considerable time (months and years) after the factors that have caused them have changed or ceased.

Of considerable importance to the level of Lake Michigan-Huron is the precipitation and amount of water in Lake Superior, which drains into Lake Michigan-Huron. That is, the advent of a dry period on Lake Michigan leading to a lowering lake levels can be either enhanced or ameliorated, depending upon the precipitation conditions (and basin supply) on Lake Superior. The worst possible situation, of course, for low lake levels is to have dry conditions on both lakes at the same time, as well as on the other lakes. The correlation of the average annual precipitation values of Lake Superior with those of Lake Michigan Basin revealed a coefficient of +0.68 for the 1901-1987 period.

The analysis of the precipitation conditions on the two lakes was based on data for 1854-1900 (when few weather stations existed), and 1901-1986 (when more stations existed and the data are considered better). Table 3 presents an analysis based on when the Lake Michigan 12-year precipitation conditions were classed as dry or wet.

Table 3. Precipitation Conditions on the Lake Superior Basin When Excessively Dry or Wet 12-Year Periods Existed on Lake Michigan

Dry Period on Lake Michigan	Percent of Lake Superior Conditions for same 12-year period		
	Dry	Wet	Neither
Early, 1854-1900	54	13	33
Recent, 1901-1986	85	6	9
Wet Period on Lake Michigan			
Early, 1854-1900	0	79	21
Recent, 1901-1986	0	100	0

The dry or wet periods were selected based on 8 or more of the years in the 12 years experiencing below (for dry) or above (for wet) average precipitation. The results in Table 3 indicate that when a 12-year dry period exists on Lake Michigan, it is highly likely one will exist on Lake Superior, too.

A dryness index was defined (the number of years of below-normal precipitation in any given 12-year period), and these indices on Lake Michigan for periods during 1901-1986 were correlated with those on Lake Superior. Since the dryness index takes on values of 0 to 12 (years) and the relationship is not linear, the index for each lake was replaced by its ranking in its population. The correlation of these ranks (by Spearman's test) produced a coefficient of +0.75, higher than all years correlation of +0.68. Thus, when atmospheric conditions produce below-average precipitation on the Lake Michigan Basin, similar below-normal conditions are very apt to occur on the Lake Superior Basin.

The mean levels and the outflows of Lake Michigan will also change progressively with time due to other factors. Included in these is the steadily increasing consumptive use of water in the basin, and a nearly imperceptible movement of the earth's crust in the region of the Great Lakes Basin. The tilting of the earth's crust across the basin produces slow but measurable effects on lake levels. The effect on Lake Michigan, for example, is that in the northeastern portion, land is rising with respect to land at the south end at a rate of about 30 cm per century. This is considered to be due to the rebounding of the earth's crust from the weight of the Ice-Age glaciers. The net effect of this tilting is to increase, gradually, the mean water elevation of Lake Michigan. These factors, in addition to climate fluctuations and trends, affect the lake level.

Climate Conditions During 1964-65. The record low lake levels (monthly and annual values) experienced in 1964-1965 were a direct result of below-average precipitation on Lake Michigan Basin beginning in 1961. The greatest departures from average in the basin occurred in 1963 (-1164 mm) and 1964 (-1168 mm), but with values also below average in 1961 (955 mm), in 1962 (244 mm), and in 1965 (134 mm). The annual average is 3401 mm. The delay in reaching the record lows until the winter of 1964-1965 is due to the slow response of the basin system, as described above.

It was fortuitous that during this extremely dry period on Lake Michigan there were near normal precipitation conditions on Lake Superior. The Lake Carriers Association (1964, 1965) notes how the Lake Superior waters were used to try to minimize the fall of the Lake Michigan levels. Their report states, "fortunately this very serious situation (1964 low levels) was mitigated to some extent by completion of the connecting channels program and the higher level of Lake Superior." During the latter part of 1964, outflows from that lake were substantially increased by a series of ever increasing openings of the gates in the compensating works that limit the flow of water down the St. Mary's River (connecting the two lakes). This program commenced on July 6, 1984, and increased gradually until November 10, 1964, when all 16 compensating gates (separating Superior from Michigan-Huron) were opened for the first time in a decade. The outflow had reached 125,000 cfs, aiding the navigation in the St. Mary's River (below the locks going into Lake Huron). Wide use was made of the water level prognostications issued by the U.S. Lake Survey.

Variability of Lake Levels. Of considerable importance to the consideration of the impacts of low (or high) lake levels on shorelines and shore activities is the amount of year-to-year variation in lake levels. Global climate models used to estimate future low lake levels due to a doubling of CO_2 do not provide a valid measure of this important condition, or of the type of long-term fluctuations that will accompany these extreme levels. Some modelers believe the interannual and longer term fluctuations will be large and greater than those previously experienced.

To obtain estimates of possible variability, the lake level data from the high and low lake level periods on Lake Michigan were analyzed to examine their intra-annual (seasonal) variation and their longer term variations. Table 4 presents results of a statistical analysis based on selecting the 10 periods with the lowest levels and the 10 periods with the highest levels for two durations, 3-year periods and 5-year periods. In calculating these variations, the average of the yearly mean lake height for each 3-year (and 5-year) period from 1860 to 1986 was computed. The 10 non-overlapping 3-year (and 5-year) periods with the lowest average lake heights were then computed, as well as the 10 non-overlapping periods with the highest averages. Table 4 shows four summary measures. Inspection of the medians for the coefficients of variation (Type 1) in the 10 lowest level periods reveals that they exceed those medians for the 10 highest periods, for both the 3-year and 5-year periods. The difference in variances (Type 1 or Type 2) between wet and dry periods is negligible. The differences in medians for the coefficients of variations indicate that the intra-annual variation is greater during low lake level periods than in high lake level periods.

An analysis of the rate of change of lake levels before low level periods was also made. There were eight discrete 5-year low periods during the 1860-1986 period, and these are listed in Table 5 along with the mean levels during each period. The average change for the 3-, 5-, and 10-year periods preceding each low is shown. These reveal downward trends for all the 3- and 5-year preceding periods, and the lowest lows (1923-27, 1933-37, and 1962-66) were all preceded by the largest rates of change in the 3 and 5 years preceding them. This indicates some information on the development of low-level periods is contained in the rate of change of levels preceding lows.

The changes in levels prior to low level periods were tested against all other changes using the Wilcoxon test. The rates of changes for 3 and 5 years before 5-year lows was found to be larger than the usual changes, and the differences were highly significant with p values of 0.01. Hence, multi-year decreases in levels of the type shown in Table 5 should be indicative of a potential 5-year low in the lake levels.

Table 4. Measures of Intra-Annual Variation in the Lake Levels of Lake Michigan, During Periods of High and Low Lake Levels[1]

Measures of variation for 10 lowest 3-year periods

From	3-yr average	CV type 1	Variance type 1	CV type 2	Variance type 2
1933	576.17	1.29	0.91	0.15	0.12
1963	576.19	1.74	1.14	0.33	0.20
1925	576.63	2.21	1.14	0.31	0.16
1936	576.70	2.07	1.27	0.31	0.22
1957	577.12	2.23	1.09	0.28	0.16
1939	577.27	1.41	0.80	0.15	0.11
1930	577.47	3.55	1.20	1.16	0.15
1922	577.64	2.20	1.22	0.34	0.22
1966	577.70	1.97	1.20	0.32	0.18
1948	577.81	2.59	1.52	0.48	0.29
	Medians:	**2.14**	**1.17**	**0.32**	**0.17**

Measures of variation for 10 highest 3-year periods

From	3-yr average	CV type 1	Variance type 1	CV type 2	Variance type 2
1860	581.10	1.53	1.36	0.18	0.18
1884	581.08	1.54	1.08	0.15	0.13
1876	580.66	1.94	1.11	0.25	0.21
1985	580.60	2.06	1.27	0.25	0.18
1863	580.54	2.25	0.90	0.29	0.11
1881	580.40	2.24	1.26	0.26	0.21
1973	580.20	1.61	1.18	0.22	0.18
1887	580.03	2.26	1.25	0.38	0.17
1869	580.01	2.64	1.85	0.56	0.41
1873	579.93	2.00	1.34	0.27	0.26
	Medians:	**2.03**	**1.25**	**0.26**	**0.18**

(Table 4, continued)

Measures of variation for 10 lowest 5-year periods

From	5-yr average	CV type 1	Variance type 1	CV type 2	Variance type 2
1933	576.29	1.29	0.90	0.15	0.11
1962	576.65	2.56	1.14	0.58	0.17
1923	576.94	2.44	1.13	0.40	0.17
1937	577.08	2.36	1.06	0.30	0.18
1958	577.49	3.28	1.28	0.56	0.24
1929	577.66	4.80	1.32	2.05	0.23
1946	578.14	2.89	1.54	0.57	0.30
1941	578.18	2.86	1.23	0.65	0.25
1966	578.21	3.15	1.21	0.66	0.19
1954	578.27	3.80	1.23	1.03	0.19
	Medians:	**2.88**	**1.22**	**0.58**	**0.19**

Measures of variation for 10 highest 5-year periods

From	5-yr average	CV type 1	Variance type 1	CV type 2	Variance type 2
1860	581.08	1.53	1.19	0.15	0.15
1883	580.91	2.29	1.30	0.25	0.20
1874	580.41	2.56	1.09	0.31	0.18
1984	580.29	2.59	1.25	0.47	0.18
1862	580.14	2.80	1.08	0.52	0.16
1879	580.08	2.42	1.12	0.35	0.17
1972	579.99	2.56	1.39	0.33	0.25
1870	579.92	2.58	1.56	0.50	0.32
1866	579.65	2.50	1.45	0.39	0.26
1887	579.63	3.06	1.17	0.56	0.16
	Medians:	**2.56**	**1.22**	**0.37**	**0.18**

(1)The explanations of the statistics in each table:
Col. 1: start year
Col. 2: average of yearly average lake level for the 3- or 5-year period
Col. 3: coefficient of variation (maximum in period, less minimum in period)
Col. 4: variance of monthly levels in period
Col. 5: average annual CV (maximum less minimum in one year period, averaged over all years in the period)
Col. 6: average annual variance over period

Table 5. Average Rate of Change Preceding Low Lake Level Periods of 5-Year Duration

Period From	Period To	Average Level (ft)	3-Year Period Low Level Lows	5-Year Period Low Level Lows	10-Year Period Low Level Lows
1878	1882	580.02	-0.09	-0.05	0.03
1895	1899	578.28	-0.05	-0.12	-0.22
1911	1915	578.28	-0.07	-0.14	-0.06
1923	1927	576.94	-0.35	-0.36	-0.17
1933	1937	576.30	-0.21	-0.35	-0.06
1946	1950	578.14	-0.17	-0.01	0.12
1962	1966	576.65	-0.24	-0.25	-0.27
1977	1981	578.94	-0.14	-0.21	0.03

Land Use. Relevant to the interpretation and transfer of the findings from this case study of the effects of low lake levels on the Illinois shoreline are the actual land uses found along the relatively short segment of 101 km (63 miles). Table 6 shows the distribution of shoreline as to land use and how it compares with the land use around the remaining parts of Lake Michigan. Most of the shore is beach (largely manmade) although about 30 kilometers are glacial bluffs.

All major land uses except agriculture were sampled by the Illinois shoreline, the focus of this study. Thus, certain results, as they relate to recreational, industry/commerce, and residential frontages should be potentially transferable to other urban areas around Lake Michigan (and the other lakes). An example of the small undeveloped shoreline area along the Illinois shoreline near Zion is portrayed in Figure 2. These largely undisturbed areas further reveal the effects of periods of higher and lower lake levels. The "beach ridges" from periods of oscillating lake levels in the past 2,000 years are revealed by the land forms and the alignment of the land cover. The periods of extremely higher and lower potential lake levels believed due to climatic fluctuations over the last 2,500 years have been investigated by Larsen (1985).

Table 6. Percentage Distribution of Shoreline Land Use on Lake Michigan

Land Uses	Illinois Shoreline (%)	Lake Michigan Total Shoreline (%)
Recreation	43	11
Industry/Commerce	19	6
Residential	34	33
Agriculture	0	20
Forests/Undeveloped	4	30

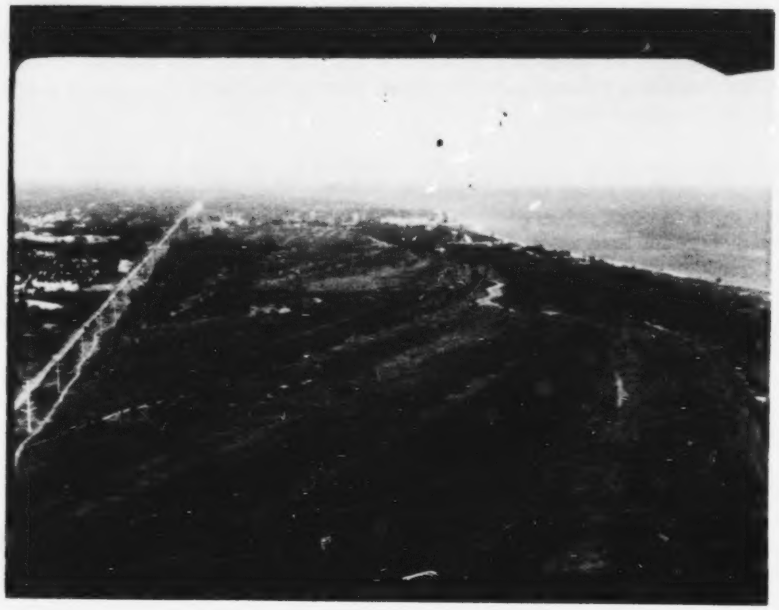

Figure 2. Beach ridged (near Zion, Illinois) left by periods of higher lake levels due to climate fluctuations in past 2,000 years.

Effects and Adjustments to Low Lake Levels in 1964-1965

Due to the data limitation problems already noted and the general lack of detailed historical records of activities by corporate and most public institutions, extensive, highly quantitative assessment of all effects of low levels was impossible. However, two areas of effects and adjustments could be assessed in detail. Hence, we chose to do (1) a general effect analysis using the information largely from interviewing (with some support from the newspaper content analysis and public records; and (2) detailed socioeconomic analyses for areas where detailed loss and adjustment data could be obtained. Thus, a general, semi-quantitative descriptive assessment of the effects in all areas has been developed, and more detailed socioeconomic assessment of effects has been conducted for two effect areas. These are described in subsequent sections. The results of the newspaper content analysis appear in the Appendix.

General Effects on the Great Lakes. Before considering the specific impacts of the 1964-1965 low lake levels on the Illinois shoreline area and related activities, it is appropriate to consider the broader context of low (as well as high) lake levels throughout the Great Lakes Basin. Society has now so developed its use of the Great Lakes that in essence any fluctuations in lake levels create a problem. Thus, low lake levels are both advantageous and disadvantageous to different impacted physical and human sectors. High lake levels act to reverse the impacts, in general. No one level condition is seen as optimum, other than the unlikely possibility of achieving a single level that remains essentially constant except for the seasonable variations. In general, high lake levels are of value to two major sectors: navigation and shipping, and to hydroelectric power generation. Conversely, most shoreline owners are seen to benefit from low lake levels. However, the existing shoreline environmental conditions (wetlands, shallow groundwater levels, and habitats) suffer from lower levels. These types of general basinwide impacts of lower levels on the lakes should be taken into consideration when examining the impacts from the 1964-1965 low lake levels on the 101-km frontage of Illinois along Lake Michigan.

Effects and Adjustments on the Illinois Shoreline. The effects and related adjustments resulting from the low lake levels along the Illinois shoreline during 1964-1965 were sorted and categorized into seven groups. The groups include:

1. Shore and near-shore physical effects.
2. Effects on transportation and shipping.
3. Recreational impacts.
4. Effects on industry and commerce.
5. Impacts on water management, supplies and drainage.
6. Land use.
7. Institutional.

The effects on physical features and related structures of the shoreline were extensive and of mixed values. One of the positive effects was the expansion of the beaches. Figure 3 notes this type of expansion around the groins of one of the Chicago area beaches.

Several negative effects of low levels along the shores were found. These included making harbors and their inlets shallower, and effects on pleasure boat and ship traffic. Figure 4 shows an entrance to one of the urban harbors, which has become sufficiently silted to require dredging for use. The results of this problem are further treated under shipping and recreational issues.

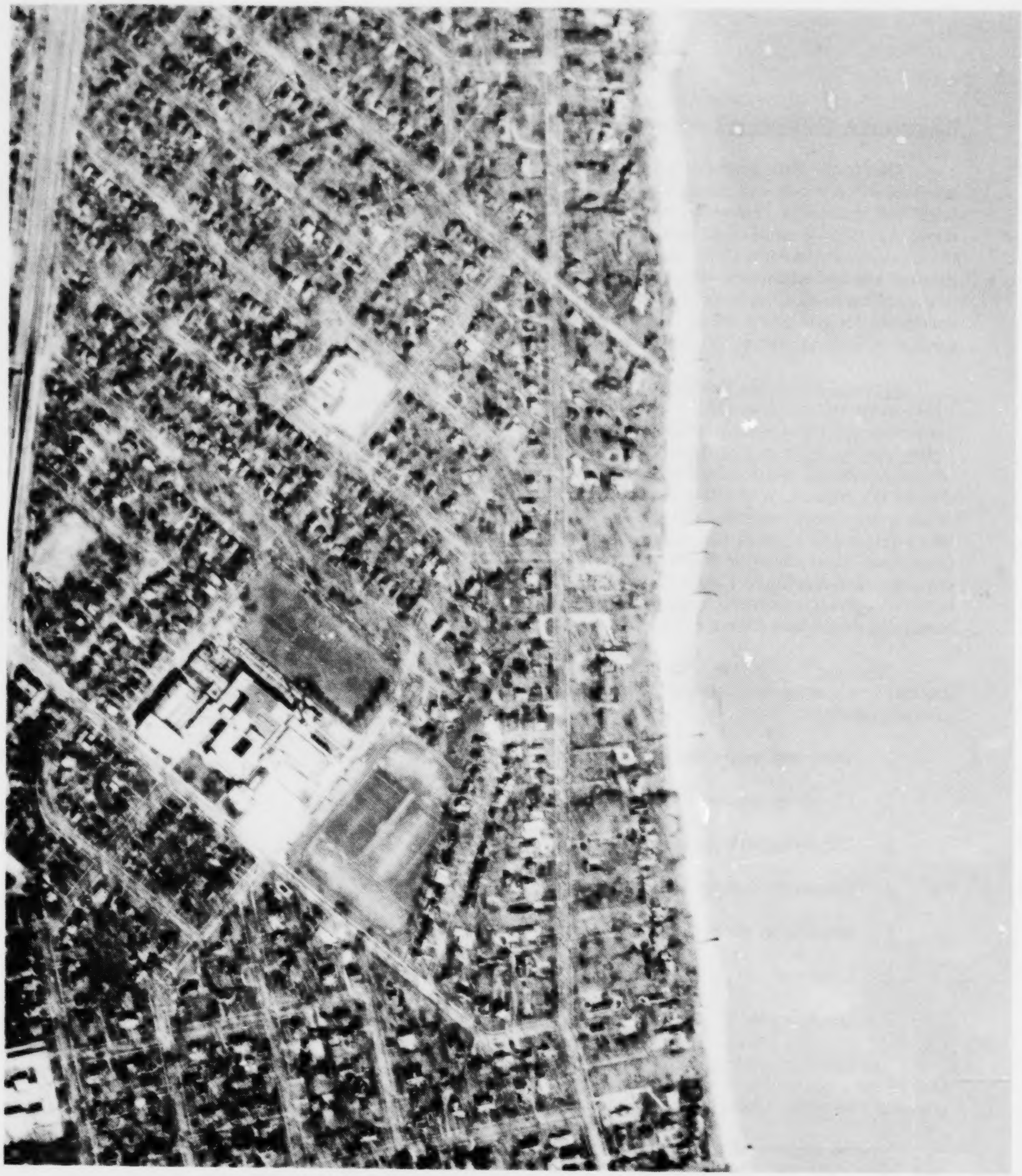

Figure 3. Expanded beaches due to extensions lakeward along groins due to low lake levels, April 1964.

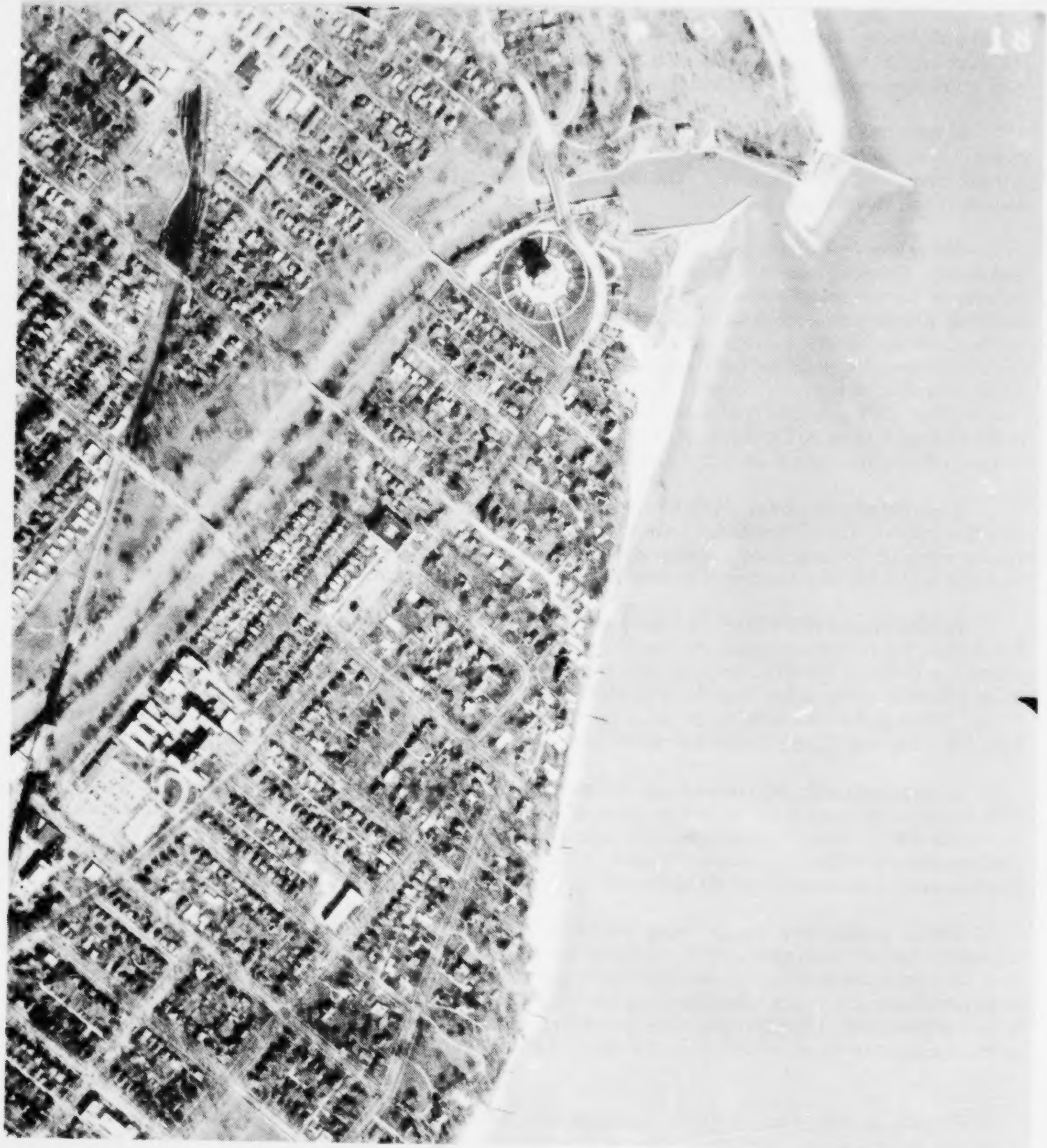

Figure 4. Harbor Channel (Wilmette Harbor) silted in March 1964.

Another physical impact along the shoreline of the lower lake levels, coupled with onshore winds, is the movement of beach sand and the formation of dunes, as shown in Figure 5. These new dunes later protected the shore against high-water conditions and storms. The effects on the wetlands and habitats north of Chicago were considered nominal, largely because the period of low water was confined to 2 years.

A more major physical effect to structures along the shoreline concerns damage to harbor and shore protection structures. The impact of low, then high, lake level interactions on the protection structures is such a major one that a separate special investigation of this problem was conducted. It is reported on in a later section of this chapter (see page 28).

The primary effects on transportation and shipping related to the low lake level areas occurred in harbors and canals. Dredging was required in certain harbors, presumably in addition to the normal annual dredging, because of the low lake levels. However, 1964 and 1965 records of the Corps of Engineers (who handle the dredging in major ports) make no mention of the effects of the low water on their harbor maintenance operations for the Calumet Harbor, Chicago Harbor, Chicago River, or the Waukegan Harbor. However, assessment of the annual dredging costs for the Calumet Harbor showed an increase of $160,000 in 1965 over that in 1964 ($284,000), an 85% increase. Special 1965 dredging costs in Waukegan Harbor were $38,000 and this occurred in April-May 1965, presumably as a result of the low-water problems. No evidence of added costs for dredging in the Chicago Harbor or Chicago River were found. Furthermore, there were no beach erosion control projects launched during this period, evidence that that was not a problem in these low-water periods.

A second impact relating partly to transportation was inflow of the water into the Chicago River and Canal diversion system. This system diverts Lake Michigan water to help sustain flow and the levels of the Illinois River system adequate for barge transportation and sanitation needs. It was reported that the lowest lake levels were such that minor problems occurred in sustaining adequate diversion during early 1965.

A third impact related to lower ship loads. Records could not be obtained for various lake carriers for this period, but experts indicated that loads carried on lake carriers were reduced between 5 and 10%. This indicates a necessity for more frequent trips and higher costs. Problems due to the low flow of the St. Mary's River (which connects Lakes Superior and Michigan-Huron) were reported (Lake Carriers Association, 1964-1965). These problems existed in the Michigan-Huron side and were addressed by greater diversion of water from Lake Superior by the Corps of Engineers.

Recreational activities received mixed impacts. Problems were related to shallow water in harbors and their inlets for pleasure craft. In certain cases, additional dredging was done to private and local urban inlets and small-craft harbors. This included Montrose, Belmont, and Jackson Harbors of the Chicago Park District. Docking was a problem as shown in Figure 6. In certain cases, docks were extended, and some were lowered. Ladders were constructed to get from the existing docks to boat level, generally as individual costs.

On the positive side, the swimming beaches along Chicago were widened. However, a major new beach (Montrose Beach) was constructed on the north side of Chicago during the early 1960s. Large volumes of much sand were imported to construct this huge beach. Subsequent higher lake levels in the 1970s led to the erosion of this expensive new beach. Sand from this beach has been scoured and moved several hundreds of meters out from the lakeshore. Plans to pump this sand back to the beach are being developed. Another recreational problem related to the launching ramps for pleasure craft. Several had to be extended to reach the edge of the water.

Impacts to private industry and commerce were difficult to isolate. Clearly, entities depending heavily upon lake carriers to obtain or ship supplies or products were hurt. Shipments were more frequent (with lighter loads), and the cost of raw materials and supplies reportedly increased by 10 to 15%. Local lake shipping companies were hurt. The loads carried had to be reduced because of the shallower harbors, and experts reported that these problems enhanced the carrying of raw materials on regional railroads, as opposed to doing so on lake carriers.

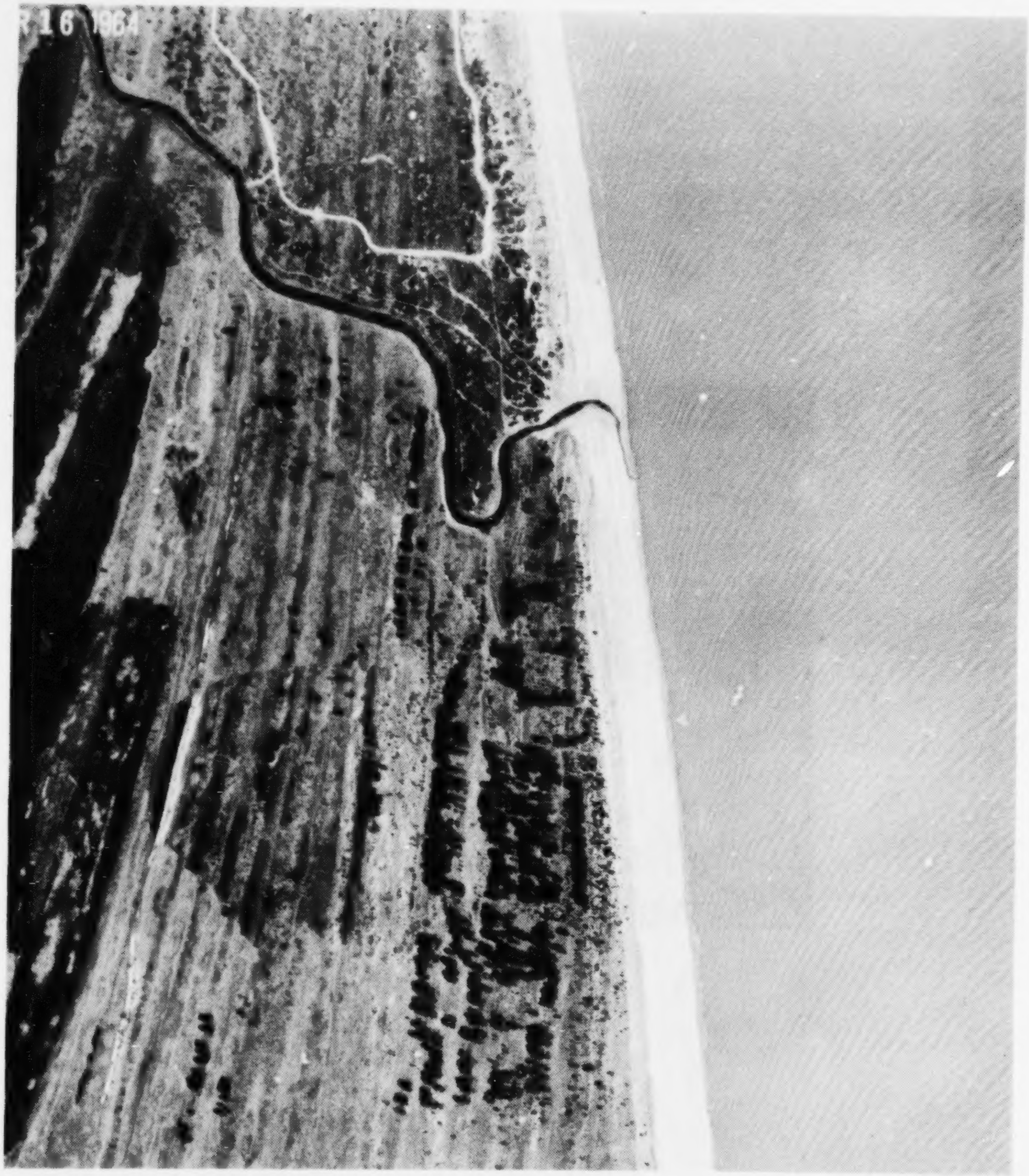

Figure 5. Sand dunes forming due to low lake levels and wind action (Illinois Beach State Park, 1964).

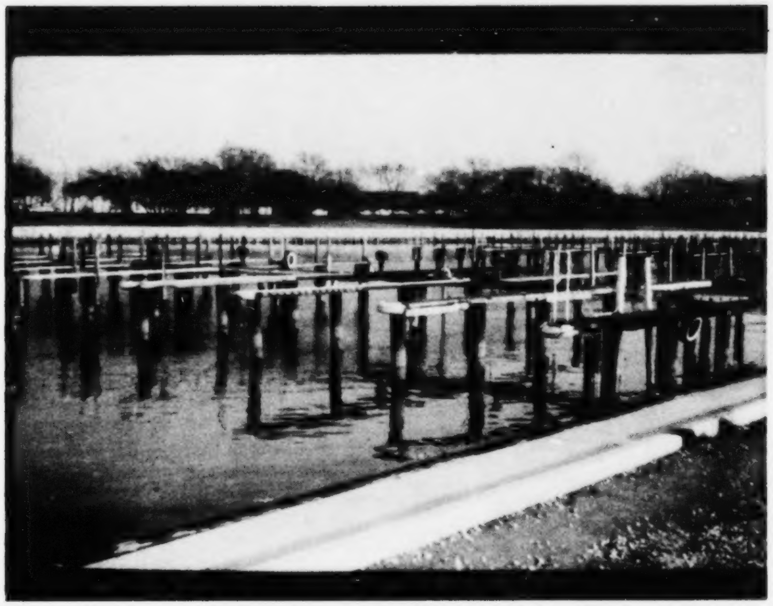

Figure 6. Docking facilities at Wilmette Harbor during record low lake levels in April 1964.

Dredging companies benefited due to increased harbor and dredging. Problems also developed because of the difficulty of finding proper areas to dispose harbor sediment considered polluted. This added to the costs of dredging and disposal, and in turn cost the local communities and local and state government more for dredging than in past years.

Effects on water management and exchange systems were considerable. In certain cities depending on lake water supplies, intakes had to be extended, such as at Evanston. In certain instances, intake levels had to be lowered, and in other instances additional water intakes were built (at three communities). Outfalls for stormwater drainage were also exposed in certain communities. At Highland Park, a major drainage line had to be extended 2,000 meters at a cost of $400,000. Certain cooling ponds along Lake Michigan also had to be dredged because of insufficient depth.

The primary impact on the land use related to the lower lake level related to the wider beaches. As noted above under impacts on recreation, this enhanced the size of public and private beaches along the lakeshore. However, the additional beach space offered the opportunity to construct various structures closer to the lakeshore. This "encroachment" occurred at locations along certain of the suburbs extending north of Chicago. The socioeconomic and policy ramifications of this encroachment during low lake levels was the subject of such considerable impact that it too is the subject of a separate detailed investigation. Again, as with the problem to lakeshore protection systems, this problem developed because of the low lake level followed by higher lake levels: thus, a "delayed effect." One needs to recognize that persistent lower levels of Lake Michigan would produce "delayed effects" in environmental conditions, with lowered groundwater levels and greatly altered wetlands.

The institutional impacts and adjustments to the low lake levels and their related problems were considerable and occurred at all levels of government. Internationally, concerns about the low lake level problems led to conferences in both the United States and Canada during 1964. As a result, the International Joint Commission (IJC) convened hearings in May 1964 in Chicago and Sault Ste. Marie. The U.S. and Canadian governments assembled and called for a "reference," an in-depth study by the IJC of the problem with possible solutions. The reference was issued in October 1964. In turn, the IJC established an International Great Lakes Levels Board on December 2, 1964 (International Great Lakes Levels Board, 1973). This Board was to undertake necessary investigations to provide in-depth advice on lake levels and their control. This assignment took nearly 10 years to complete, with the report issued in 1973. Interestingly, by the time of publication, the lake levels had gone from the record lows of 1964-1965 to new record high levels in 1973, the year the report was issued. The report provides information about the broad impacts of low lake levels, and in particular on the economic effects of variations about the mean levels of the Great Lakes.

Most communities along the lakeshore had to react in various ways to the low lake levels, both in positive and negative ways. Increased costs of local dredging and harboring were met, and water management systems were altered as noted. Mayors, city engineers, and water and sewage treatment officials had to deal with a variety of problems and advantages related to the bigger beaches and more difficult problems of water exchange.

The City of Chicago, the Metropolitan Sanitary District of Greater Chicago, and the State of Illinois were involved in concerns and adjustments relating to the diversion needs and low levels. Chicago Park District installed a new major beach (Montrose Beach). The Corps of Engineers was involved in greater dredging.

The Center for the Great Lakes instituted a series of meetings related to the lower lake levels, and developed a long-term program to assess land management techniques and to provide information on what types of lakeshore techniques had failed and succeeded (Great Lakes Reporter, 1987). Basically this report was related to the "delayed" impact of the low lake levels of the 1960s and the subsequent high levels in the 1970s and 1980s, and the necessity to consider methods (including structures) to deal with problems both at the low and high end of the level spectrum.

In private sector institutions, some of the impacts and adjustments noted were the profits of private dredging firms; however, after the low period the number of firms decreased. Consulting engineering firms dealing with lake issues (harbors, docks) received enhanced business, and the number of firms increased. Certain small shipping companies were sufficiently hurt to lead to their termination or amalgamation into larger firms.

The diversion of lake water done by Illinois into the Chicago and Illinois River systems, and for water supplies in the Chicago urban area, was not affected by the low lake level. The subject of the Illinois diversion has been an issue of contention among the lake states since the 1920s. The U.S. Supreme Court reduced the diversion, which was 10,000 cfs, in the 1920s to 3,100 cfs by 1938 following the Court's decree of 1930. Subsequent decrees have monitored and allotted the diversion to 3,200 cfs, including domestic pumpage. This amount of diversion counts for an annual 0.23-foot decrease of the level of Lake Michigan. The diversion depends upon gravity flow from the lake into the river and canal system. If lake levels had fallen somewhat lower than those achieved in 1964-65, natural inflow to the rivers would have been difficult in the cold season (winter) period of lower lake levels. Lowering of Lake Michigan could become a major impact at Chicago, requiring major pumping systems, extensive dredging, and costly new lockages to put Lake Michigan water into the drainage system.

In summary, the institutional impacts were diverse, generally very troublesome and costly, often taking years to comply or complete. The situation, given only a 2-year low lake level period, suggests that future persistently lower levels will create institutional problems beyond the ability of our current institutions to address in any satisfactory manner.

Damage to Shoreline Protection Structures. One of the major effects of the record low levels in the 1960s, and subsequent increases in the lake levels to much above average levels during the early 1970s and mid-1980s has been to create major damages to most of the wooden shore protection works of Chicago.

In the early part of this century and extending up through the 1920s, the City of Chicago expended more than $100 million on the development of its shoreline park system. Roughly $1 billion was spent on landfill along the Lake Michigan shoreline and in constructing the park system (Mayer and Wade, 1969). This transformation of Chicago's lake front ranks as one of the world's most vast public works relating to waterfronts and to the development of parks, recreational facilities, and transportation systems (Real Estate News, 1927). Much of the 38-km frontage owned by the City of Chicago along the lakeshore (nearly 40% of the total Illinois shoreline) was extended from its pre-settlement shoreline eastward, ranging in distance from tens of meters to more than 3,000 meters eastward in certain locations. More than 1,300 acres of new park lands were added south of the city center (Loop) where no parks existed.

This was accomplished by the construction of a series of protection works along the lake frontage, often built of wood and steel and filled with rock and cement, with varied structural designs over the entire 38-km frontage. Behind these protection devices, the area was filled with sands brought in from the lake and with soil. Extremely valuable new property was created. Those portions of the shoreline devices that essentially remained below water from the time of their construction (1890-1930) up to the low-water period of the 1960s were exposed to the air during the 1964-65 low-water period. Dry rot set into the planking at that time. Subsequent increases in lake levels to record high levels in the early 1970s and then ever higher levels in the 1980's with accompanying wave action from storms have acted on the weakened wooden areas that experienced dry rot, helping lead to destruction of many of the wooden pilings.

The City of Chicago has established an investigatory commission (Chicago Shoreline Protection Commission, 1987). The Commission has made an in-depth assessment of the damages to the shoreline protection structures along the 38 km lake front owned by the city. This report sets forth a range of technical options and alternatives to obtain a new and long-term shoreline protection system. It cites the "rapid and effective emergency responses by the city, the Chicago Park District, and the Army Corps of Engineers" to protect the public from immediate threats, to keep the city functioning during critical storms, and calls for a program of local, state, federal, and private sector cooperation to begin the process of comprehensive repairing of the accumulated damage. Again, this damage is partly the result of two things: (1) the sequence of record low levels in the 1960's (and the dry rot to the wooden support structures), and (2) the subsequent high water levels of the 1970s and 1980s, coupled with the incidence of major storms during the higher levels. That is, the high water levels increased the power of the lake to erode the shoreline, particularly during storms.

Wind and wave action of the lake erodes the shoreline regardless of water levels, and systematic maintenance and repairs are needed as erosion occurs. The Commission's report also notes that the shoreline protection system has not been systematically maintained over the past 50 years (since being completed in the late 1920s). As a result, it is severely weakened and undermined.

A single storm during the high water levels (on February 8, 1987) with high winds (60 mph) caused enormous flooding along the lakeshore, causing the closure of major avenues and Meigs Airfield; the evacuation of property along the shore; and the flooding of sewers, basements, and underpasses, including Navy Pier and a major water purification plant of Chicago. Severe shoreline damages occurred with much park land eroded. Costs of emergency responses to Chicago and cleanup were substantial, exceeding $2 million. Physical damage to city property such as the Navy Pier and the water purification plant exceeded $1 million.

The portion of these damages or of the costs to repair or replace them, resulting directly from the rot that developed during the low lake levels cannot be assessed independently. It is a part of the problem. Estimates indicate that more than 60% of the lakeshore devices made from wood were initially damaged by the dry rot incurred during the 1964-65 low lake levels. These will eventually have to be replaced. The latest figures indicate that the estimated construction costs for rebuilding the damaged shoreline protection system is $843 million.

Encroachment Land Use Problems. The lowering of lake levels during 1964-1965 resulted in new wide beaches. This highly valuable "new land" led to the construction of buildings closer to the new beach areas. This construction largely involved houses, apartment buildings, and condominiums built in places along the lake shore north of Chicago. These structures, built into the new beach areas, have subsequently become areas of extreme damages when higher lake levels occurred in the 1970s, within a decade after the record lows. Again, as shown in the prior section on effects on lakeshore protection works, the long-term (decadal) type oscillations of lake levels (low then high) have led to this encroachment problems. One area of encroachment along the lake front is being investigated in detail as to the effects on the shore, the owners and the community where the encroachment occurred. Permitting relating to lakefront land use changes have been tightened, and this issue promises to be a future key issue in a future with lower lake levels.

The movement of the lake edge from 1964 to 1987 was measured using the aerial photographs of the Illinois State Geological Survey. An example of their map analyses of shorelines for the Zion map quadrangle is shown in Figure 7. This depicts both shorelines. This area last was typically 150 meters wide, and the total land available in 1964 and underwater in 1987 is 0.9 km^2 in the mapped area of Figure 7. This helps illustrate the problems of encroachment.

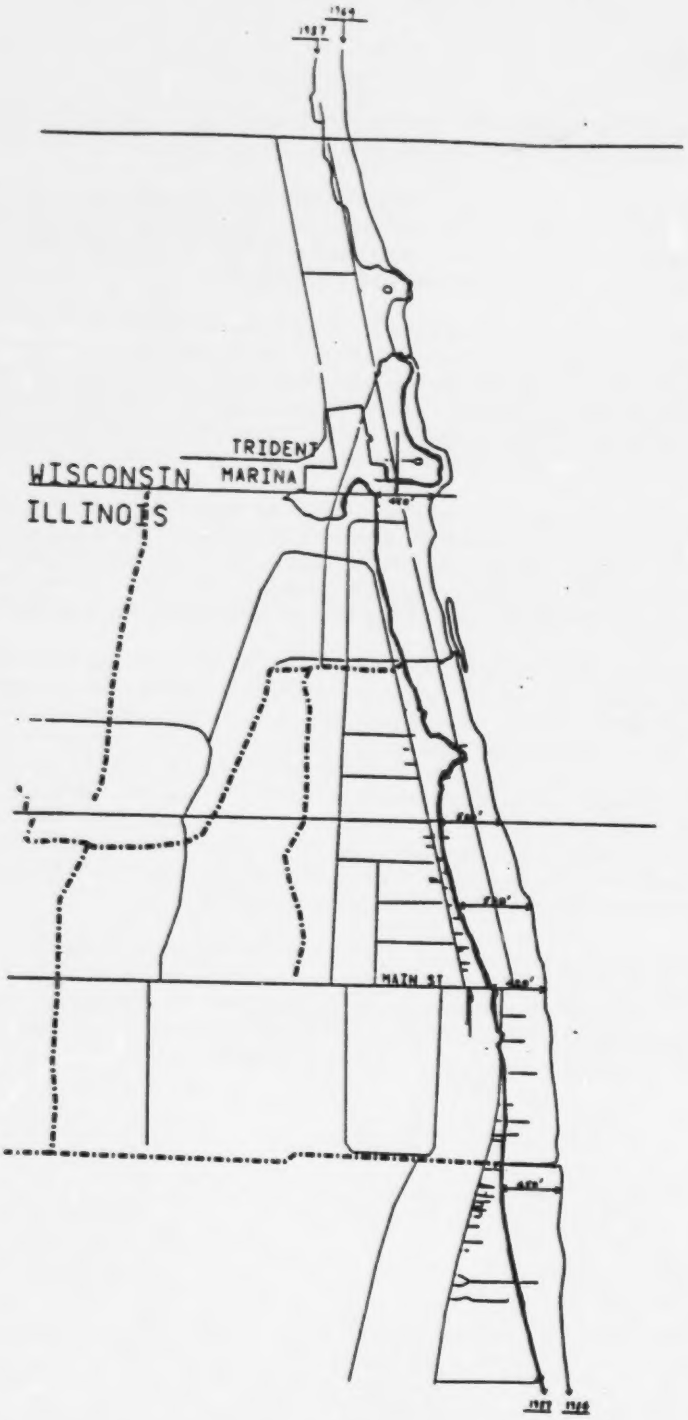
1964
1987
TRIDENT
MARINA
WISCONSIN
ILLINOIS
MAIN ST
1987
1964

Figure 7. Comparison of the 1964 and 1987 Shorelines as Displayed on the Zion Map Quadrangle (Illinois Geological Survey).

CHAPTER 4

INTERPRETATION OF RESULTS

SUMMARIZATION OF RESULTS

This project has already led to the offering and acceptance of three scientific papers relating to various results. These papers, their authors, and place of presentation are as follows:

1. "Impacts and Adjustments to Record Low Lake Levels: The Illinois Case," Stanley A. Changnon, Annual Conference on Great Lakes Research, Canada, May 1988.
2. "Climatic Change: The Knowns and Unknowns," Stanley A. Changnon, National Research Council Colloquium on Great Lakes Water Levels, Chicago, March 1988.
3. "Impacts of Record Low Lake Levels of Lake Michigan," Stanley A. Changnon, G. J. D. Hewings, and S. Leffler, American Water Resources Association Symposium, Milwaukee, WI, November 1988.

These papers will help transfer the results of the project to the user public including the scientific community. They each treat portions of the research of the project.

SIGNIFICANCE OF FINDINGS

Review of the findings indicate that the most significant social and economic impacts resulting from the record low lake levels of Lake Michigan during the early 1960s occurred as a result of the subsequent return to higher water levels 10 to 20 years after the low levels had occurred. The two most major effects, extensive damages to shoreline protection facilities and the encroachment of buildings and facilities to the new beach areas, both occurred because of the low levels and then the upward swing of lake levels to 1.5 meters above the record low levels of the early 1960s. Clearly, if lake levels of 1964-65 had remained low with normal seasonal oscillations of 30 cm, the impacts to the existing shoreline property would have been much less. However, other detrimental effects would have developed in groundwater conditions, wetlands and shoreline habitats, shipping, harbors, and water available for diversion and other uses.

Two important aspects of this study and its results are relevant to the general issue of climate impact assessment. First, it was impossible to get adequate, extensive quantitative historical data to make in-depth economic assessments of many effects. Newspaper content analysis is inadequate, and necessary records of public and private institutions are essentially unavailable (lost or destroyed). It would be particularly beneficial to assess the impacts of the prolonged low lake levels from the 1920s to the 1930s, if the data existed. This suggests the need to develop and use economic models to simulate the effects of low levels.

Another apparent significant result relates to the general economic impacts of "low lake levels." Although hard to quantify, those relating to the low lake levels of 1964-1965 did not appear to be relatively high. The more costly impacts related to encroachment of structures into the exposed beach areas and the damage to the shoreline protection structures occurred only as a result of the combined action of high levels (and storm-enhanced wave action) following within a few years, the low levels. Thus, the **more major economic impacts are a result of large lake level fluctuations, not just low levels.**

CHAPTER 5

SOCIOECONOMIC AND ENVIRONMENTAL IMPLICATIONS

NEEDS FOR PHYSICAL INFORMATION AND RESEARCH

Certain implications can be drawn at this time from the available results. The use of the 1964-1965 results as an analogy for the impacts from future lower lake levels was limited because these results have shown the period to be too short to have allowed certain physical changes (erosion and sediment processes) to reach equilibrium and too short to attain many social and institutional adjustments expected from much lower levels of Lake Michigan.

One result of the physical assessment of the low lake levels performed for this study is that the period of about 1910 to 1940 would be an informative period to model for estimating low lake level physical effects. Although not the record lowest levels, this is a more prolonged period of 20 years of decline to reach a 12-year period (1930-1941) of prolonged low lake levels. Research on effects during this time period should be considered.

Results of the study establish that the magnitude of effects of lower levels of the Great Lakes will likely depend heavily on the magnitude of the longer-term (decadal) oscillations of lake levels around the new mean low level with a significant climate change. The oscillations in levels means that controlling land use will have to be developed (see Policy chapter). The ability to set wise limits for structures and thoroughfares attempting to encroach in the new exposed land area will depend on the expected future oscillations of lake levels around the lower average levels. This will be made difficult by the fact that the lower levels will probably develop over decades, such as the slow decline in the lake level from 1900 to 1940 (see Figure 1).

Climate modeling studies should address the subject of possible climate fluctuations and resulting lake level oscillations apt to occur with any given lake level (high or low). Results will be essential to a reasoned approach (1) to develop means to rect to fluctuations in lake levels, and (2) to limit encroachment. Climate modeling of atmospheric changes and effects on the physical (hydrologic) conditions beyond the basin is essential.

The issue of water diversion, both in and out of the basin, will hinge on the new future values of the hydrologic cycle (precipitation, runoff, evaporation), both in and out of the basin. A drier and warmer climate in Illinois and Wisconsin will lessen runoff in the Illinois River transportation system. This will lead to needs for more lake water for diversion and greatly altered channels and lockages, both **major technical and policy issues**. A drier climate will heighten controversies over the diversion at Chicago.

Any permanent reduction in lake levels whether 0.5 or 2.5 meters below today's base level, will necessitate dredging to deepen commercial and recreational harbors and channels. Since the deposition of toxic materials has occurred in all commercial harbors (and some recreational harbors), the ultimate deposition of these large volumes of polluted sands and other bottom materials will be a major problem and one requiring both physical research and socioeconomic studies.

MAJOR POTENTIAL IMPACTS

Estimations of potential impacts of conditions due to lower lake levels in future years are difficult to quantify with certainty. Values from three global climate models for the Great Lakes (based on increased atmospheric CO_2 and other trace gases) all indicate future lower lake levels but with widely varying heights. The predicted future levels of Lake Michigan from the models for the Illinois shoreline (and expressed as below the 1951-80 average or base level) are: (1) 0.86 meter (2.8 feet); (2) 1.25 meters (4.5 feet); and (3) 2.52 meters (8.2 feet). The climate scenario based on a 12-year period of the driest years of 1900-85 yielded a level of Lake Michigan that was 0.38 meter below the average.

Speculations offered herein about future impacts and adjustments from these lower levels must be considered within the context of several limitations in the global climate models. Thus, a short discussion of important key features of all three models is offered for assessing the likelihood of the estimated impacts and adjustments offered herein. All models are broad treatments of regional conditions and most modelers are skeptical about using the model-derived values for estimating regional charges. Regardless, all models show (for the Great Lakes Basin) more moisture in the atmosphere, an increase in high clouds, and a 4°C increase in air temperature. Their predictions of precipitation levels differ greatly both in the magnitude of change and placement of change. One model shows a basinwide increase in precipitation of 10%. Some models show increased precipitation in the west (Superior and Michigan Basins) and decreased in the east (Ontario Basin). One model expects the interannual variability of precipitation to be greater than in today's climate regime. The interdecadal variations will probably be large as the climate changes rapidly.

In conclusion, the projected changes in climate (and in lake levels) by all models could be wrong, and their use is considered scientifically risky to use at the regional level. These concerns and lack of other relevant information required assumptions before we could estimate certain future impacts.

Assumptions

First, the doubling of CO_2 and the effects on future climate conditions leading to predicted future levels of Lake Michigan will be achieved by a process that produces a near linear, continuing decrease of lake levels requiring at least 50 years and up to 100 years to achieve.

Second, since the decadal size oscillations around these future levels due to climate fluctuations are not predicted with any certainty in these models, and since this is very important in the impact analyses, the oscillation was assumed to be in the current range, 1.5 meters between the maximum and minimum values over any 100- or 200-year base period, or ± 0.75 meters around the mean level.

A third assumption is that relevant current laws and regulations relevant to shoreline impacts will be retained. Society, in essence, would be continuing its current trend to more control and regulation of natural resources.

A fourth major assumption is that the use of immediate frontage on Lake Michigan for beaches and harbors will continue, as will the use of the lake for water supplies and for deposition of storm runoff.

Further, we remind the reader that the study was limited to the Illinois shoreline with its largely urban-type frontage. We also have not addressed the water quality issue in any substantive way because of the magnitude of the issue and the lack of information on the qualities of lake waters under the three climate scenarios.

Impacts

The model prediction of a future lake level of 0.86 meters below the 1951-80 average closely matches the lake level achieved during the 1964-65 record low period, 0.92 meters. Of course, an oscillation around that future average would exist at times, occasionally driving the level more than one meter below the current average. Most adjustments made to the low levels during 1964-65 are known (see Chapter 3). Experts in harbors, lakeshore facilities, and water facilities concluded that the 1964-1965 adjustments would largely satisfy the 0.86-meter predicted decrease in level. There would be increased harbor dredging; slightly expanded beaches; and alterations in slips and piers. There should be relatively few adjustments to serve water exchange needs (intakes and outfalls). Moreover, many adjustment costs would be met as normal facility replacement costs. Increased dredging and new facilities would lead to $75 to 100 million (in 1988 dollars) in added costs over 50 years.

The effects of the predicted future lower lake levels of 1.2 meters and 2.5 meters were more difficult to quantify and required more speculation since these were beyond levels experienced since settlement of the Great Lakes. As noted in the assumptions, attainment of these values was assumed to occur after 50 years of gradual lowering of lake levels. This assumption is very important in estimating potential economic effects. Efforts to speculate on effects of the 1.25- and 2.5-meter lower levels focused on the direct effects on the shoreline and its immediate facilities.

Recreational Facilities and Harbors. Lakeshore experts agreed that major impacts would occur to pleasure boat harbors and facilities. Many harbors have wooden slips and docks, and the continuing exposure over time of the below-water portions of these structures will produce dry rot. A major impact is that at 1.25- or 2.5-meter decreases in lake levels, all slips and docks would have to be replaced. A calculation estimation of this at one recreational harbor facility led to a cost (in today's dollars) of $2 million. However, considering the time of change involved, 50 or more years, and that the lifetime of these structures is typically 30 to 40 years, at least one normal replacement would be necessary and occur anyway in the 50-year period of changing climate. Thus, the cost of modifying slips and docks to adjust to the lower lake levels could be partly handled by normal replacement costs, not as new, additional costs. Knowledge of the continuing shifts in water levels was seen as likely to lead to the acquisition of floating docks. In fact, these could be seen as becoming common for the pleasure boat facilities along Lake Michigan.

The second major area of impact to the pleasure boating facilities was to the harbors. Some experts predicted that some pleasure boat harbors would become "unusable," particularly with the 2.5-meter reduction. All harbors can be adjusted to handle the 1.25-meter reduction. Specific harbors considered to be nearly unusable without major dredging were Wilmette, North Point, and Winter Harbor. The cost of deepening harbors through dredging was seen as necessary and quite high to handle both new future levels. Costs for dredging and deposition of harbor materials considered to contain toxic materials was 20% higher (1988) than for handling nontoxic materials. Estimated values for the 1.25-meter reduction were $3 to 5 million per harbor, and for the 2.5-meter departure, $5 to 10 million per harbor. One expert estimated the cost of pleasure harbor dredging in Illinois at $100 million to address the 2.5-meter reduction in level. The estimate presented in Table 7 is $75 to 100 million, and assumes that all harbors would be dredged and maintained.

A third area of impact to harbors for pleasure boat facilities related to bulkheads. In many areas, harbor edges must be defined by vertical metal sheeting. In both the predicted future levels, it was estimated that all existing sheeting along about 4 miles of harbor shores would need to be driven to deeper levels at a cost of $750 per foot. In those harbors with natural shorelines, and to maintain harbor size, new piling would need to be installed along another 4 miles of shoreline. The calculated costs range from $15 million (1.25-meter level) to $35 million (2.5-meter level).

Hotels and restaurants dependent on lake frontage for "lake access" for attracting patrons would suffer. No economic estimate of this impact was developed but it could be a major problem to selected businesses.

Commercial Harbors. Commercial harbors would also experience major effects. We assumed that all must maintain an 8-foot (2.4-meter) draft to be effective for lake carriers. The costs to dredge and modify the major commercial harbor facilities (Calumet, Chicago, and Waukegan) would be sizable. One expert indicated that the high cost of keeping the harbor open at Waukegan (at 2.5-meter lake level) might not be justified by values gained, leading to its closure, and possibly the Chicago harbor costs would not equate to its value and lead to its closure. The cost of dredging the harbor at Waukegan ($5/yard) was calculated to be $3 million to meet the 1.2-meter level. Furthermore, breakwaters would be difficult to support and new supports would have to be constructed. The dredging costs for the commercial harbors and canals, as accumulated over time, was calculated at $108 million for a reduction in lake level of 1.25 meters, and $210 million for a level 2.5 meters lower (see Table 7).

Table 7. Estimated Economic Impacts of Lowerings of the Levels of Lake Michigan Over a 50-Year Period (1990-2040)

Costs in millions of 1988 dollars to address future lake levels at indicated depths below average level of Lake Michigan (1951-1980).

	1.25 meters lower	2.5 meters lower
1. Recreational Harbors		
Dredging	30 to 50	75 to 100
Sheeting	15	35
Slips/Docks	20[*]	40[*]
2. Commercial Harbors		
Dredging	108	212
Sheeting/Bulkheads	38	38
Slips/Docks	40[*]	90[*]
3. Water Supply Sources		
Extending urban intakes	15	15
Wilmette Harbor Intake	1	2
4. Beaches		
Facility relocations	1-2	1-2
5. Outfalls for Stormwater		
Extensions and modifications	2	4
TOTALS	$270 to $292 million[*]	$512 to 540 million[*]

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[*] Some costs could be partly covered by normal replacement expenditures over the 50-year period of changing level.

Dredging in all commercial harbors and canals would be a problem, particularly for the polluted materials in their bottoms. This greatly increases the costs for disposal for the polluted material. This would be a particular problem for the two local "Areas of Concern," the Waukegan Harbor, and the Grand Calumet River. These were identified in 1973, along with 40 other locations, as particularly heavily polluted areas (Great Lakes Water Quality Board, 1987). Costs of dredging (Table 7) included higher costs of the polluted sands in these two areas.

All slips and docks in commercial harbors would have to be rebuilt due to dry rot and to lower levels for access. However, due to obsolescence and normal depreciation over 50 years or more, normal replacement would occur with costs not totally related to the climate-induced reduction in lake levels. The estimated replacement costs shown in Table 7 are indicated to be attributable to normal replacement costs. Costs of driving existing bulkheads deeper was calculated as $35 million over the 50-year period. New bulkheads in a few areas would cost $2.6 million.

Beaches. Another area of impacts relate to recreational beaches. In this study, we assumed that the lowering of lake levels would not lead to construction of major new shore protection works to protect beaches. The benefits of lower lake levels to beaches are not insignificant. The underwater slopes away from current beaches along Lake Michigan and Illinois range from 2:1 in fine grain areas to 40:1 in coarse sand areas, with an average of 20:1. Detailed bathymetric maps (depth of lake bottom from lake levels) were used to calculate the amount of land to be gained from the lower lake levels. Figure 8 is an example showing the contours below low water datum, the current shoreline, and historical (pre-1932) shoreline of Lake Michigan before barriers were built and fill used. Calculations for the beachfront gained between Fullerton Parkway and Ohio Street (on this map) indicated 0.1 km^2 for the 1.25-meter drop and 0.5 km^2 for the 2.5-meter drop in levels. The calculated increase for the 43 km of beach frontage based on the decrease of 1.25 meters in lake level was an additional beach area of 1.12 km^2, and the 2.5-meter reduction would create 3.24 km^2 of additional beach area. Certain beach facilities would be relocated and/or constructed for an estimated cost of $1 to $2 million (Table 7). No monetary benefit was assigned to the added beaches. Moreover, the benefits of the lower levels would be appreciable to the bluff shore area north of Chicago where expensive residential areas exist and where major bluff erosion occurs in high waters. Major expenditures (> $20 million) by communities and individuals have occurred in the recent high-level periods (Changnon, 1987), and these would end.

Environmental Impacts. Several of the aforementioned impacts relate to problems of an environmental nature. This includes the issue of dredging and deposition of polluted sediments/sands of harbors and canals. A major environmental problem of lower lake levels will be changes in the hydrologic cycle. The shallow and deeper groundwaters interacting with the lake will be reduced over time. Lowered groundwater levels will detrimentally affect existing wetlands and lessen ecosystem production. Overtime, new wetlands will develop if the rate of lake level fall is sufficiently slow. Polluted groundwaters in the urban area will percolate into the lake, and in turn polluted lake waters will percolate into aquifers; the net result will be reduced lake and groundwater quality. Thus, it seems likely that unless agricultural and urban pollutants now entering the lake are greatly reduced, the overall quality of the waters of Lake Michigan at Chicago will be further diminished under a drier-warmer climate scenario.

Water Intakes. Another area of future impact relates to water intakes in the lake to serve municipal and industrial water supplies. Most of these are positioned well beneath the lake surface to be free of ice and to maintain sufficient head for pressure because they are gravity fed. Along the area north of Chicago there are 14 major intake systems (several cities have two intakes at different locations). Analysis of these for varying future levels of Lake Michigan revealed different outcomes. At the reduced lake level of 1.25 meters below the current average, three of the intake systems would have to be altered at a total cost of $2.8 million (see Table 7). With a reduction in lake level of 2.5 meters (the worst possible outcome), we find that six systems would require a range of extensions adding up to a cost of $7.4 million ($900/30 cm, in 1988 dollars).

Water Supplies. A major impact of the predicted warmer and drier climate with the lower lake levels and poorer water quality, will be a reduction in water supplies. Population growth and the more arid climate will increase usage and demands for water (1) to serve Chicago and its suburbs, (2) for industrial processing, (3) for

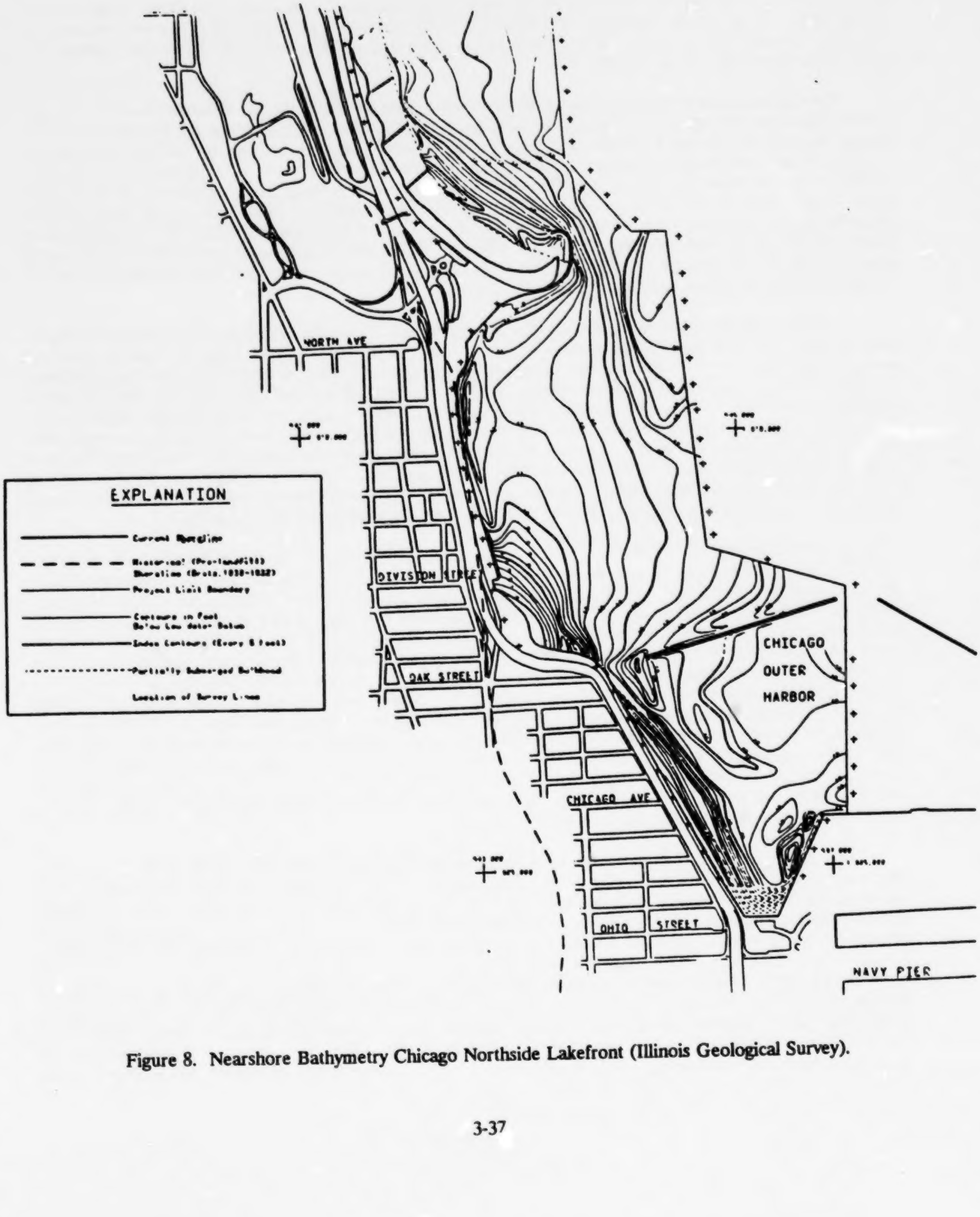
EXPLANATION
Current Shoreline
Historical (Pre-landfill)
Shoreline
Project Limit Boundary
Contours in Feet
Below Low Water Datum
Index Contours (Every 5 Feet)
Partially Submerged Bulkhead
Location of Survey Lines
NORTH AVE
DIVISION STREET
OAK STREET
CHICAGO AVE
OHIO STREET
CHICAGO
OUTER
HARBOR
NAVY PIER

Figure 8. Nearshore Bathymetry Chicago Northside Lakefront (Illinois Geological Survey).

cooling of power plants (such as at Zion), (4) for shipping needs in the Chicago River and Canal system and the Illinois River, (5) for sewage treatment, and (6) for hydroelectric power generation at Lockport (southwest of Chicago). Cohen (1987) projected 30 to 40% increases in municipal water uses in the Great Lakes Basin as a result of the predicted climate change.

The lake as a source would be hard pressed to meet these increased needs. Pressures to maintain lake levels by the other lake states and Canada would cause serious national and international controversy over any Illinois requests for increased diversions of lake water. Increased diversion seems an unlikely outcome, as revealed by the controversy and strong opposition to the idea of increasing diversion during the summer drought of 1988 to help increase the flow of the Mississippi River. The effects on demand/supplies of water supplies would then extend to groundwater sources. For example, the suburban communities would likely turn to groundwater sources (most have wells) to supplement the inadequate lake supplies, which will prove difficult to obtain and at best be very expensive. This shift, if sizable, would lead to decreased groundwater levels and to more mining already present in some suburbs. This impact also will create interstate conflicts related to increased groundwater use and the effect on lake supplies.

Another area of impact from greatly lowered lake levels and decreased runoff relates to the Chicago River and Canal system. This complex system now depends largely on gravity flow from Lake Michigan to maintain water levels in the river and canal system. Problems with the low lake levels in 1964-1965 led to the installation of a major pumping system at Wilmette Harbor to ensure the supply of water out of the lake into the upper reaches of the system. The predicted reductions of lake levels below 1 meter would bring major requirements to deepen the Wilmette Harbor system, including its entrance, and the necessity for lowering the pumps to meet the 1.2- and 2.5-meter lake levels. The operation of the river system with lower lake levels would be very concerned about loss of water at the Chicago River outlet, leading to possible restrictions on the frequency of entry and exit of boat and ship traffic. Another effect would be reduced water released for power generation at Lockport. Costs for the Wilmette Harbor adjustments in pump levels are shown in Table 7.

A related problem that will develop from the warmer-drier climate conditions will be the effects on the hydrologic cycle of the streams and rivers in the Illinois River Basin. Presumably this area adjacent to Lake Michigan, and tied to the lake through the water diversion at Chicago, will experience substantially decreased runoff due to the suspected climate changes. The Illinois River is a major transportation artery controlled by a series of locks and dams between Lockport (near Chicago) and its junction with the Mississippi River near St. Louis. The level of flow in the river to satisfy barge usage is maintained by the diversion of 3,200 cfs of water at Chicago, the maximum amount allowable under the current U.S. Supreme Court decrees. Basin runoff for the arid climate outcomes will be reduced by at least 20%. **This will make the river system including the locks unusable.** Alternatives include deepening the river and rebuilding the lockages, diverting more water from Lake Michigan, or loss of the barge transportation. The first case represents an exorbitant expense. The added diversion seems unlikely with the lower lake levels and extreme pressures against increased diversion. The resulting inability of the river system to function in its current fashion might lead to increased shipping by railroad. Pressures would be great to change the lockages and dredge the navigation channel. Costs for these impacts were not estimated but would be sizable.

Water supplies from Lake Michigan for public usage and certain industrial needs could be seriously affected by major degradations in water quality if they occur with the projected lowerings of lake levels. The magnitude of this potential problem is unknown but it would increase water treatment costs. A warmer climate and lower levels of the lake would also cause lake water temperatures to become higher than at present. The amount of change is unknown but if sizable, it could affect cooling water needs of power plants and industry.

In the net, the future warmer and drier climate will lead to increased needs for water to serve Chicago and the Illinois area. However, the ability of Lake Michigan to provide added water for these demands (or to sustain the current diversion level) likely will be blocked by institutional forces in the Great Lakes Basin. Further, deep groundwater aquifers in northeastern Illinois, already subjected to excessive drawdowns, will not be able to meet the future needs. This situation could very adversely affect the growth and economy of the

Chicago region. It seems likely that effects to develop new sources in the more shallow groundwater aquifer (heavily mineralized and partly polluted) will be pursued as the only resource.

Outfalls. Another effect relates to outfalls and outlets for storm rainwater for communities along the lakeshore. For both the 1.25- and 2.5-meter lower lake levels, all 28 existing major outfalls (1 meter or larger diameter) would have to be extended, ranging from 50 to 150 meters in length. This would lead, as shown in Table 7, to additional costs to local communities of $2 to 4 million.

Encroachment. The final area of potential impact analyzed as possible from the major reductions in lake levels relates to encroachment of buildings, thoroughfares, and other structures in the newly formed beach areas that will occur. This regulatory/policy issue would, under current regulations, be controlled by the fact that Chicago has a lakefront ordinance, and by the fact that the State of Illinois vigorously enforces the lakefront usage permit process. The State of Illinois claims ownership of all lands to the edge of the "record high water level." Thus, private land owners cannot modify or replace land lost due to high water erosion. In essence, if this theme of strong governmental control was maintained over the 50+ years required for the predicted lake reductions, the newly formed lands would remain under governmental control and would be free from serious encroachment for buildings and other structures. However, is this a likely societal outcome? Will this type of protective legislation develop around other shoreline areas?

A key to this issue will be vigorous enforcement. During recent high lake levels several instances of "self-help" construction were done without permits and the State did not prosecute.

Other Possible Impacts. Another implication open to speculation relates to the possible advent of a widespread warmer and drier climate in the United States. If this occurs, an "out migration" from the Sun Belts, which will become more like "Hot Belts" can be expected. This migration will undoubtedly include movement into the Great Lakes Basin. A warmer climate will reduce ice coverage on Lake Michigan including shore ice, and this may lead to more rapid shoreline erosion than currently occurs.

Another potential impact of much lower lake levels and its detrimental effects to basinwide shipping would be the potential for increase of shipping by railroads. Commercial lake fisheries would presumably be hurt by lower lake levels, warmer water, and fewer fish.

Table 7 presents the best, albeit qualitative, estimates of the economic influences of the two model predictions of greatest reductions in lake levels. In summary, these show that along the Illinois shoreline (101 km) the effects of lower levels on harbors, water supply sources, beaches, and urban outfalls would lead to costs between $270 and 292 million for the 1.25-meter fall, and between $512 and 540 million (1988 dollars) for the 2.5-meter reduction. Experts in lakeshore issues consider these costs to be justified for maintaining the high valued harbors and beaches of this major urban area.

Conclusions. The economic effects of one GCM prediction of a mean lake level 0.86 meters down from the current average, and accomplished gradually over 50 years, is seen to not have serious economic consequences (<$100 million over 50 years), and to be partly accommodated as part of normal maintenance and replacement activities and costs. However, the potential effects on water demand and supplies would be serious. Maintaining supplies to meet increased demands with less lake water (and of poorer quality) would lead to interstate and international controversy and in turn, increased groundwater usage of an already meager source.

A projected climate change leading to a reduction of the mean lake level of 2.5 meters produces much more serious economic impacts. Hence, the character and magnitude of the economic impacts relating to a changing climate and the lowering of lake levels are very sensitive to the amount of decrease predicted to occur, and in turn to the seasonal-decadal climate-related fluctuations in levels envisioned around the new mean lake level.

These results reveal that the global climate models and climate scenarios they have developed (and their related assumptions) for the Great Lakes Basin are extremely critical to estimating future impacts, adjustments, and policy actions. Differences in these models make very major differences in the impacts. Hence, the ability to undertake major revisions of policy at this time responding to the future increases in trace gases and their effects on climate appears difficult, at least as far as the Lake Michigan-Illinois situation is concerned. Economic impacts range from essentially a manageable level to major extremes, greater than $0.5 billion along 101 km of shoreline. These differences relate to different climate models. These widely different outcomes in lake levels reveal considerable atmospheric uncertainty in the outcome and in turn suggests it would be very risky to develop policy actions at this time. More firm and consistent predictions of change in climate are needed along with indications of change. However, all levels of change will create serious water supply problems and issues requiring policy actions.

A factor for recommending cautious reaction to this situation, in light of the Illinois shoreline, is that the rates of lake level change in all models do not exceed the rate that normal replacement costs, or economic life, could handle in harbor and beach facilities. In other words, a major portion of the dockage changes needed to address major reductions in lake level could be handled over a 50-year period by normal replacement costs. **However, this would require recognition and acceptance of the ongoing change.** Regardless, with the replacement costs removed, the economic effects from the two most severe predicted lake level reductions, 1.25 meter and 2.5 meters, would result in costs ranging from about $200 million to $400 million, respectively (Table 7).

Major problems would be realized in the harbors and canals (dredging, bulkheads, slips, and docks), and in the disposal of polluted wastes. The costs for improving harbors and their facilities and for extending intakes and outfalls would presumably be met largely by local communities, the state, and the federal government. Ultimately these costs would be transferred to the public.

The gains to be realized by the lower lake levels would be wider beaches ranging from 30 to 60 meters with an addition (depending on the lake level reduction) of 1 to 2 km^2 of beach area in Illinois. Fortunately, the widened beach area is likely not sufficiently increased to allow for major expansions into the beach area and the ensuing need for construction of new shorefront protection systems. The wider beaches themselves will help protect the shoreline. The private dredging and construction firms that handle harbors and their facilities, and address water intakes and outfalls, would be beneficiaries of the major reductions in the lake levels.

Future Adjustments

The potential exists for lake levels to be much lower than those experienced in 1963-1965. The GCM predictions, and the climate scenarios designed for this study, all seen as possible, show a potential for levels that will be 0.4 to 2.5 meters lower than levels experienced in 1964-1965. What are the potential adjustments that may and should occur?

A primary one relates to the need to incorporate, in all aspects of harbor and shoreline structures, and related land use, a "design for lake level fluctuations." A more permanent lower level will provide recognized gains in valuable lands, particularly along urban frontages of all the Great Lakes. This could benefit communities, recreation, and certain industries. There will likely be a major push into these lands that must be carefully weighed.

A second series of adjustments that can be predicted to occur will relate to the real and perceived needs for increased water supplies in the lakes to serve the needs of shipping, urban and industrial water supplies, and hydropower generation. This demand will create calls for increased diversion, presumably from sources in Canada, into the Great Lakes, and for decreased diversion at Chicago and elsewhere. Whether such shifts involving interstate and international negotiations and agreements can be realized seems unlikely under current institutions and legal agreements.

The additional water needed could also be potentially realized through new technologies to increase precipitation through weather modification and to reduce evaporation through various physical and chemical techniques. Exploratory and developmental research will occur in these areas.

Similarly, there will be an increased need to improve predictions of lake levels during a more stressed lake regime. Research to develop better capabilities, in climatology and hydrology, to predict climate and lake level fluctuations around a lower mean level will occur.

In summary, comparison of the more direct economic losses with the apparent gains indicates that even the worst of the projected lake level reductions will not cause unaffordable economic problems along the valuable Illinois shoreline. All the changes can be handled in an economically effective manner, often by employing normal replacement and maintenance procedures if master planning for these changes is implemented and if the decrease occurs gradually over several decades. The Great Lakes Charter (1985) contains the charge to develop a "cooperative water resources agreement program for the Great Lakes Basin." It could serve as the basis for proceeding.

The other impacts to Illinois water supplies and to environmental conditions will be major problems. The increased water demand vs. less available lake water (and of poorer quality) could greatly affect mining of the local and regional groundwater supplies. We lack the institutional arrangements and laws to address the magnitude of these problems in Illinois or in the other lake states. The water quality problem of Lake Michigan will likely become a major issue for Illinois shoreline interests including water for public consumption, industrial needs, and recreation.

CHAPTER 6

POLICY IMPLICATIONS

The future incidence of lower lake levels will greatly affect policy at the international, national, state, and community levels. Potential problems relating to lower water levels and less adequate water supplies will lead to needs, real and perceived, to divert additional supplies into the Great Lakes from Canadian sources. It will also lead to desires to increase diversion at Chicago with resulting controversies reaching the Supreme Court and international forums. The climate change will also reawaken concern over the current amount of water diverted at Chicago. The amount being diverted will be contested. The likely inability to provide waters of desired quantity and quality from Lake Michigan to serve Chicago, its suburbs, and the Illinois-Chicago Rivers system will lead to increased usage of ground water. Deep aquifers will be further depleted leading to disagreements over water mining between Illinois and adjacent states (Wisconsin and Indiana).

The effects of lower levels will reinstate dredging of all recreational and commercial harbors. Major added costs for recreational harbor maintenance and intake/outfall extensions will fall largely to local communities, and these will probably lead to an effort to seek state and/or federal support. Disposal of the polluted harbor materials from dredging will be costly and of great environmental concern, and will affect federal and state policies and enforcement strategies.

Increased widening and deepening of certain major connecting channels in the Great Lakes to allow shipping loads can be envisaged to develop as regional policy issues. All of these concerns/activities will relate to national policies and in turn to actions by federal agencies such as EPA and COE and their Canadian counterparts.

The need to resolve the problems of lower levels will also lead to research on atmospheric and hydrologic issues. This will impact the federal agencies that support research in these areas such as NSF and NOAA.

It seems likely that the problems with encroachment onto beaches, coupled with lake-level oscillations, even with relatively lower mean levels, will develop. This will likely lead to federal and/or state regulations concerning land use activities along the shores of Illinois and the rest of the Great Lakes.

Several factors could greatly alter the impacts and the policy adjustments postulated as related to the lowering of Lake Michigan levels. First, if the changes in climate lead to step-wise shifts creating sharp drops in lake levels rather than gradual changes in levels, the problems will materially increase and crisis management seems likely. We need better institutional mechanisms now to deal with the recent fluctuations (record high levels in 1985-86, and now precipitous declines).

Another factor that could alter the postulated impacts and policy actions concerns the amount of variation around the future mean lake levels. In this study of potential impacts we have assumed that the fluctuation over time (>100 years) would be equivalent to the current ± 0.75 meter; if this is much greater, a variety of other more serious impacts and different policy actions could occur.

The third factor that could greatly vary the impacts and ensuing policy actions concerns whether sizable amounts of water could be diverted into the Great Lakes in Canada to help ameliorate the effects of the lower levels. This would certainly reduce impacts and policy actions, but is probably unlikely in a more arid climate. Similarly, if new water-adding technologies were developed (weather modification or evaporation suppression), the levels of impacts and policy reactions would be changed. Warmer and drier conditions elsewhere in the U.S. may also lead to efforts to divert waters from the Great Lakes for irrigation and public water supplies.

A further factor that could influence the policy outcomes relates to the societal attitudes towards the use of lake frontage and the protection of lake frontage; should this change drastically, the policy outcomes could be altered greatly from those predicted herein.

Consideration of the impacts and adjustments that would occur to the harbors, beaches, intakes, outfalls, and transportation reveals that (1) wide acceptance of the ultimate reduction of lake levels over 50 or more years and (2) recognition of normal replacement of facilities and maintenance of harbors could be sensibly combined in a "master engineering plan" for the area. That is, wide acceptance by the scientific and engineering communities that the lake level would be gradually falling by a rate of 0.1 foot/year and that by 2050 the average level would be 2 meters lower, would be the basis for in-depth planning of all future lake-related activities. For example, the normal replacements of harbor facilities, including the slips and docks, maintenance of the breakwaters, and the installation of bulkheads could be geared to the downwind shift in lake level. Replacement of locks in the river and channel navigation systems would take into account the ongoing climate shift. In essence, many adjustments could be made in a most cost-effective manner over the 50-year period. However, a Master Plan would need to be developed to guide these activities based on wide agreement over convincing evidence of a change. This would be a major policy issue.

In the Great Lakes Charter (1985) the governors of lake states and the premiers of the Provinces committed themselves to the development of a "Great Lakes Basin Water Resources Management Program." This could become the basis for addressing the many policy issues raised by a changing climate.

We recommend that policy action for implementing such a plan, and action now in other policy areas, should begin. The wide variations of model outcomes leading to lake levels ranging from 0.86 meters to 2.5 meters lower than today's average level, produce differences in the magnitude of the economic effects but they all relate to severe water quantity and quality issues calling for policy development.

A basinwide climate change to more arid conditions in 50 years will create problems similar to those predicted for Chicago at all metropolitan areas around the Great Lakes. One envisions very large expenditures to maintain shoreline structures and facilities plus enormous conflicts over water supplies and environmental effects. The inability of the U.S. and Canada and our existing institutions to deal effectively now with recent transboundary pollution (air and water) problems in the Great Lakes Basin suggests major policy actions must occur and new institutions must develop to meet the challenge of the envisioned climate change. The Boundary Waters Treaty of 1909 will certainly undergo modification.

Acknowledgments

This study was the result of the efforts of several people. Charles Collinson, Paul Terptra, and their colleagues at the Illinois State Geological Survey provided invaluable advice, data, and materials used in this study. Jean Dennison helped prepare the text and illustrations.

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REFERENCES

Changnon, S.A. "Climate Fluctuations and Record High Levels of Lake Michigan." Bulletin of AMS, 68:1394-1402, 1987.

Chicago Shoreline Protection Commission. Preliminary Protection Options and Alternatives: Requests for Public Comment. 1987. pp. 1-33.

Cohen, S., 1987: Projected Increases in Municipal Water Uses in the Great Lakes Due to CO_2-Induced Climatic Change. Water Resour. Bull., 23, 91-101.

Corps of Engineers. Annual Report. U.S. Army, Washington, D.C., 1964. 1109-1163.

Corps of Engineers. Annual Report. U.S., Army, Washington, D.C., 1965. 1083-1135.

Great Lakes Charter, 1985: Principles for the Management of Great Lakes Policy Resources. 7 pp.

Great Lakes Reporter. Coping with Fluctuating Lake Levels. Special Report, Center for the Great Lakes, Chicago, 1987. 8 pp.

Great Lakes Water Quality Board, 1987: 1987 Report on Great Lakes Water Quality. International Joint Commission, Detroit, MI, 236 pp.

Holms N. Inventory of Lake Michigan Research Projects 1984-1987. Environmental Geology Notes 121, State Geological Survey, Urbana, IL, 1987. 423 pp.

International Great Lakes Level Board. Regulation of Great Lakes Water Levels. Report to IJC, 1973. 294 pp.

Lake Carriers Association. Annual Report. Cleveland, Ohio, 1964. 38 pp.

Lake Carriers Association. Annual Report. Cleveland, Ohio, 1965. 48 pp.

Lamb, P.J. "On the Development of Regional Climatic Scenarios for Policy-Oriented Climatic-Impact Assessment." Bulletin, Amer. Meteorol. Soc., 68: 1116-1123, 1987.

Larsen, C.E. A Stratigraphic Study of Beach Features on the Southwestern Shore of Lake Michigan: New Evidence of Holocene Lake Level Fluctuations. Environmental Geological Notes, 112, Ill. Geological Survey, Champaign, 1985. 31 pp.

Mayer, H. and R. Wade, 1969: Chicago: Growth of a Metropolis. Univ. of Chicago Press, 292 pp.

Neill, J.C. and C.-F. Hsu. "Using Non-Integer Spectral Analysis in Discerning Spatially Coherent Rainfall Periodicities." Times Series Analysis, 5:375-384, 1981.

Quinn, F. "Courses and Consequences of the Record High 1985 Great lakes Water Levels." Preprints Conference on Climate and Water Management, AMS, 1986. 281-184.

Real Estate News. South Parks Our Big Public Boon. Vol. 22, No. 10, 1927. pp. 1-7.

Wigley, T.M.L., Jones, P.D., and P. Kelly. "Empirical Climate Studies: Warm World Scenarios and the Detection of a CO_2 Induced Climate Change Induced by Radiatively Active Gases." Chapter 6, The Greenhouse Effect, Climatic Change and Ecosystems. J. Wiley & Sons, Chichester, 1986. 271-322.

APPENDIX I: NEWSPAPER CONTENT ANALYSIS FOR 1964-1965

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INTRODUCTION

During low water periods several problems commonly arise. These problems include the encroachment of buildings into high risk areas, difficulties with shipping and harbor maintenance, damage to drainage systems, and even damage to shoreline protection devices. Though these problems are well known, some are difficult to document. Building encroachment problems and damage to shoreline protection devices become apparent as the water level rises, but it is quite difficult to document damage to drainage systems, harbor maintenance, and shipping problems. In the twenty years which have passed since the record low lake levels, most official records (i.e., surveys, repair cost reports, appraisal studies, etc.) have been destroyed, misplaced, or are otherwise irretrievable. Likewise, most of the knowledgeable personnel during that time period have retired, and/or disappeared.

A search through the newspapers of the 1964-1965 period was one method used to document impacts. Newspapers are a potentially good media to search because they are easily accessible and can cover a wide range of topics. As we learned, many of the impacts of low lake levels were not perceived as problems at that time, and those that were problems, may not have been perceived as important enough to warrant an article. This approach was impractical for studying the social impacts of low lake levels. Few articles are written about too much beachfront.

The objective of this newspaper content search was to attempt to document the physical, social, and economic impacts of the low lake levels. This included looking for any incurred costs due to repairs, dredging, etc. As a secondary objective, we also attempted to identify persons who might be interviewed for more detailed information.

METHODS

A thorough examination of the Chicago Tribune (CT) and Chicago Sun Times (CST) was conducted for most of 1964 and portions of 1965. Both newspapers were available on microfilm at the University of Illinois. Unfortunately, no indexes were available for this time period, and thus the tedious task of searching each page of the newspaper was needed. A file at the Illinois State Geological Survey, based on newspaper clippings on lake related topics going back to 1970 also was analyzed. This file was used for documenting high water problems further documenting low water impacts. This file was composed mainly of CST and CT articles, but also included articles from several smaller neighborhood newspapers and a few articles from newspapers of other big cities.

Month (65/65)	J	F	M	A	M	J	J	A	S	O	N	D	J	F	MAY
Chicago Tribune	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Chicago Sun Times			X	X			X	X	X		X			X	X

Newspaper search coverage for 1964 and 1965.

DATA

Many articles during the low lake levels period (1964-1965) reported that the lakes had reached another "record low." These were often accompanied by discussions of the amount of water diverted into the Mississippi through the Chicago River or notes on the meetings of the International Joint Commission. There were 21 articles of this type (in 15 months).

The following collection of articles (pages 5-7) represents all those found which were relevant to impacts. The collection consist of articles from both the 1964-1965 search and the ISGS file. Portions of most of these articles were quite irrelevant and thus only Article #3 is complete. Articles #1-4 discuss shipping and harbor management problems that resulted from low lake levels. These articles were found during the search of 1964-1965 newspapers. The remaining articles discuss problems with Chicago's seawall. Through these problems were not discovered until recently, they stem from the low lake levels when the wood pilings in the shore protection devices were exposed to air and subject to dry rot.

ANALYSIS

Article #1 discusses both positive and negative impacts of low lake levels. It implies that shipping had been reduced significantly due to low lake levels, especially in shipments of "heavy commodities." This supplies a clue as to which industries were most impacted by low lake levels. By checking with the harbor, we learned which companies were shipping ore and limestone during this time and then contacted those companies for more information. Though only iron ore and limestone were reported on, coal mining is a significant part of Illinois' economy and it would be interesting to explore how the coal industry was affected. Also mentioned in this article are a few social impacts of the low lake levels, including increased beach size and easier access to rivers by pleasure craft.

Article #2 links low lake levels with a loss of shipping business at the Port of Chicago. It reports that overall shipments were down 20% from the previous year. This loss was mostly in the form of "general cargo" (i.e., machine goods). The cause of the decline in shipments was given as "insufficient water depth in the Calumet River" and increased competition. It should be noted, however, that the business of other port facilities was reported as up, implying that this may be an isolated case.

Article #3 reported mainly on the causes of the low lake levels. It also gave a good rule that could be used to help estimate the total amount of business lost. That is, for each inch the water level dropped, ships lost 100 tons of cargo they could have otherwise carried.

Article #4 discusses the deepening of the Calumet River in a flight to curb the 20% loss of shipping at the Port of Chicago (Article #2). The total cost of the project was estimated to be $3.5 million.

Article #5 reports on the findings of a panel of engineers who recently (1987) examined Chicago's seawall. They found that "11 miles of seawall and 2.5 miles of breakwater need immediate repair." An estimated total cost of $200 million was given. This is the first article which directly linked low lake levels to the deterioration of the seawall. It reported "during a low water period in the 1960's, the pilings were exposed to air and dry rot set in."

The final two articles discuss the findings of an underwater survey of Chicago's seawall which was compiled using sonar aboard the research vessel "Neecho." Article #6 reports that the deterioration of the wall had allowed waves to scour caves 12 feet into the shore and wash large fill rocks out 40 feet from beneath the seawall. Article #7 reports that repair work on the seven worst miles will cost "between $37 million and $111 million."

These articles also supplied us with the names of important contacts to whom we referred to for further information.

RESULTS AND DISCUSSION

The purpose of this search was to analyze newspapers as a help in documenting the physical, social, and economic impacts of low lake levels. First, how good was this method in detecting and defining the impacts of low lake levels?

By far the most costly impact of the low lake levels was the damage caused to Chicago's seawall. This impact was not detected, or at least not perceived as a problem, until record high lake levels began to cause major damage. However, once this problem was detected, it drew significant attention.

Probably the second most costly impact of the low lake levels was the difficulties inflicted upon the shipping industry. These problems manifested themselves in the form of a decrease in the shipments of manufactured goods and also in the form of increased harbor maintenance. This problem received attention during the low lake levels. The articles found on this subject helped define the problems.

During the recent high water period, the subject of water encroaching towards housing structures received coverage, but was never linked to low lake levels. The low lake levels caused these problems by lulling people into building in an area perceived as low risk. None of the articles written on this subject discuss when the housing unit(s) were built. The newspaper content analysis yields no evidence to show the low lake levels caused problems with drainage devices or water supply systems. The search did identify some of the social impacts such as valued larger beaches.

CONCLUSIONS

Is a newspaper search useful in assessing the social and economic impacts of low lake levels? The number of articles found was disappointingly low, and the articles found only barely documented the many impacts of low lake levels. Moreover, this was an inefficient method of documentation.

APPENDIX II: QUESTIONNAIRE FOR ASSESSING EFFECTS OF LOW LAKE LEVELS

A semi-structured interview process was used with those who had been involved in various lake-related activities during the early 1960 period of low lake levels. These interviews were largely conducted over the telephone, although certain person-to-person interviewing was done.

The initial phase of the interview involved establishment of institutional credentials. This was followed by a description of the project including its goals and objectives. This was followed by a description of why the person interviewed was selected. At this stage, we sought their willingness to proceed with the interview.

Following acceptance of willingness to be interviewed, a well-known example of an impact was presented; typically a case of encroachment of buildings. This was used to illustrate that the impacts could be direct (physical), occur at the time of the low water levels or later, or could be secondary or tertiary in the socio-economic fabric. This portion of the interview was used to allow the person being interviewed to think and recall events of that time.

At this stage of the interview, obvious or possible impacts in the arena of the expert were illustrated as introductory statements to general questions of events that developed in 1964-1965. Depending upon the interviewee's willingness, further probing questions were asked. Questions typically focused on specific phenomena, periods of time of resulting events, ensuing costs (or gains), and adjustments. Another area of inquiry after the open discussion questioning related to questions about availability of records that could be investigated to allow us to find more specific details of dates and financial impacts.

At the end of the interview there were two standard questions in addition to a "thanks" for cooperation. One of these was related to a personal visit to get more information, or willingness to have us call back to get more information. If a visit was seen as desirable, dates and place were arranged. The other ending interview question related to any thoughts about persons or places to get further information on the subject.

EFFECT OF CLIMATE CHANGE ON SHIPPING WITHIN LAKE SUPERIOR AND LAKE ERIE

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FINDINGS[1]

The potential effects of climate change on the Great Lakes shipping system were evaluated through the use of a Great Lakes shipping model of six specific locations in Lake Erie and Lake Superior developed by Engineering Computer Optecnomics, Inc. (ECO). The ECO Great Lakes Shipping Model simulated water level reductions of from 1 to 5 feet, and showed that the changes in water level and ice cover on the Great Lakes will have an effect on shipping due to climate changes predicted by various climate change models. The primary effect of water level reduction will be an increase in shipping costs due to reduced vessel-carrying capacity. The reduction in ice coverage will extend the shipping season, and the additional shipping days will be adequate under most scenarios to compensate for the cargo capacity that was lost due to reduced water levels. Dredging the locations to maintain existing depths is an achievable alternative but would be dependent on similar dredging and potential new construction in other parts of the Great Lakes system such as the Sault St. Marie locks and the St. Marys and St. Claire Rivers.

Six locations were used for the shipping model: Two Harbors, Duluth/Superior, and Whitefish Bay in Lake Superior; and Toledo, Cleveland, and Buffalo in Lake Erie. Two scenarios of climate change yielded 1- to 2-foot drops in the water level in Lake Superior. The shipping model showed that a 1-foot reduction in water level would cause a 1.6 to 3.3% decrease in cargo capacity for the present fleet at locations in Lake Superior. There would be a corresponding increase in costs per ton carried of 1.6% to about 3.4%. The reduction in ice coverage would allow the shipping season to be extended. Up to nine additional shipping days would be required to make up for the reduced carrying capacity. The climate simulation models predict that between 40 and 60 days may be added to the shipping season due to reduced ice coverage enabling the present cargo demand to be accommodated. With the extended season, shipping costs per ton would decrease from the water reduction scenario to about 1 to 2%.

Two climate scenarios for Lake Erie showed a 2- to 3-foot drop in water levels, while a third showed a drop of greater than 5 feet. A 3-foot drop in water level for locations in Lake Erie would result in a 5 to 13% reduction in cargo capacity, with a similar increase in cost per ton transported. Up to 40 additional shipping days would be required with about 70 additional available days predicted. Costs under both the reduced water level and ice coverage scenario show a combined increased cost of 2.9 to 7.5%.

Dredging costs to maintain the present location channels would range from about $1.4 million for Two Harbors to over $20 million for the Duluth/Superior location. These costs do not include system costs such as other channel deepening and lock modification, which would be required for the dredging in the individual location to have any system benefit, nor do they reflect additional costs that may occur due to construction of additional disposal sites and associated environmental issues.

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[1] Although the information in this report has been funded partly by the U.S. Environmental Protection Agency under contract no. 68-02-4532, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

Scientists studying the effect of increasing concentrations of greenhouse gases have tried to predict how quickly, and to what extent, atmospheric temperatures may rise. For analytic convenience, the convention has been to examine the implications of a doubling of carbon dioxide (CO_2) levels. In 1979, the National Academy of Sciences concluded that such a doubling would lead to an increase of 1.5 to 4.5°C in global air temperatures. This increase in air temperature and the associated increase in water evaporation could result in a decrease of water level within the Great Lakes.

A decrease in water levels on the Great Lakes could have a significant impact on the many industries that ship their goods through the various locations on the Great Lakes. For instance, even a relatively small drop in the water level would mean that some vessels would no longer be able to operate on the lakes at their existing drafts. Larger decreases in water levels would mean that fewer and fewer vessels would be capable of traveling between locations at their design drafts. The lessened drafts result directly in reduced cargo-carrying capacity per trip and, with the ice-limited shipping season, a potential reduction in present system total carrying capacity.

Conversely, this same increase in air temperature could result in less severe winter ice in terms of thickness as well as duration of the ice season. This reduction in winter ice could result in an extended shipping season for many of the vessels on the Great Lakes.

This analysis will examine the effect of the increased temperature levels on the Great Lakes shipping industry. The analysis will be based on a computer model of the shipping patterns and port characteristics of selected locations on the Great Lakes; namely, Duluth/Superior, Two Harbors, and Whitefish Bay within Lake Superior and Toledo, Cleveland, and Buffalo within Lake Erie. These locations were selected to represent the breadth of conditions within the two lakes. Our study will focus on the change in carrying capacity and associated change in costs; and will address the changes due to reduced water levels and ice coverage, and the combination of reduced water levels and reduced ice coverage. In addition, an analysis of dredging required to maintain port water levels at present conditions, so as to maintain present system port capability, will be presented.

CHAPTER 2

METHODOLOGY

The analysis utilizes a Great Lakes shipping model developed for the specific locations derived from ECOSHIP and ECOPORT, marine databases developed by Engineering Computer Optecnomics, Inc. (ECO), of Annapolis, Maryland, and integrated with the results of scenarios of changes in lake level and ice cover due to global warming provided by the Great Lakes Environmental Research Laboratory. A graphic representation of the model is shown in Figure 1.

A number of assumptions have been made in applying the model to the climate change analysis.

- The base line for the shipping patterns of the specific locations is the 1985 calendar year. The lakes shipping system shows significant variations from year to year. These significant variations in year-to-year operations dictate the use of a single representative year rather than a series of years to isolate the impact of the climate change. The year 1985 is used in the model since it is representative of average Great Lakes' water levels. It is also the latest year for which data are available on a consistent basis. Only those vessels in the base line period are assumed to carry cargo in any future period, and no accommodation is made for newer ship designs or other technological changes and/or responses to the potential reduced water levels.

- The model does not assume change in future cargo shipments. Rather, it assumes that cargo shipments will be constant for the period in question. It does estimate cargo capacity limitations as a result of changes in water levels and ice coverage.

- The dredging analysis treats the individual locations in an independent manner. The analysis does not attempt to rationalize the different water levels that are projected for either Lake Superior or Lake Erie.

- The model operates in 1-foot increments of water level change. The available input data are not precise enough to allow fractional changes and still provide realistic model solutions. The analysis does, where appropriate, interpolate the data to agree to water levels projected by the climate change scenarios.

While specifically tailored for the purposes of this analysis, the model is sufficiently general to enable the above assumptions to be modified in the future. The main input elements of the shipping model are described below.

MODEL ELEMENTS

Port Dimensions. As indicated above, six locations will be used for this analysis. The locations are shown in Figure 2, and their principal physical characteristics are shown in Table 1.

Port Vessel Transit Patterns. Each location exhibits different mixes of vessel class transiting the port due to individual cargo requirements and importantly, the capacity of the geometric configuration of each location area to accept various sizes of vessels. The vessel mix for each location is given in Table 3 as a function of draft. This table illustrates previous comments that locations tend to utilize the largest vessels that can be accommodated in its boundaries.

Vessel Economics. The cost to transport cargo in a vessel is normally expressed in terms of dollars per ton carried. The method for ascertaining that cost is determined by amortizing the cost of the vessel over its economic life, adding the daily operational costs such as fuel and personnel for the number of days in operation,

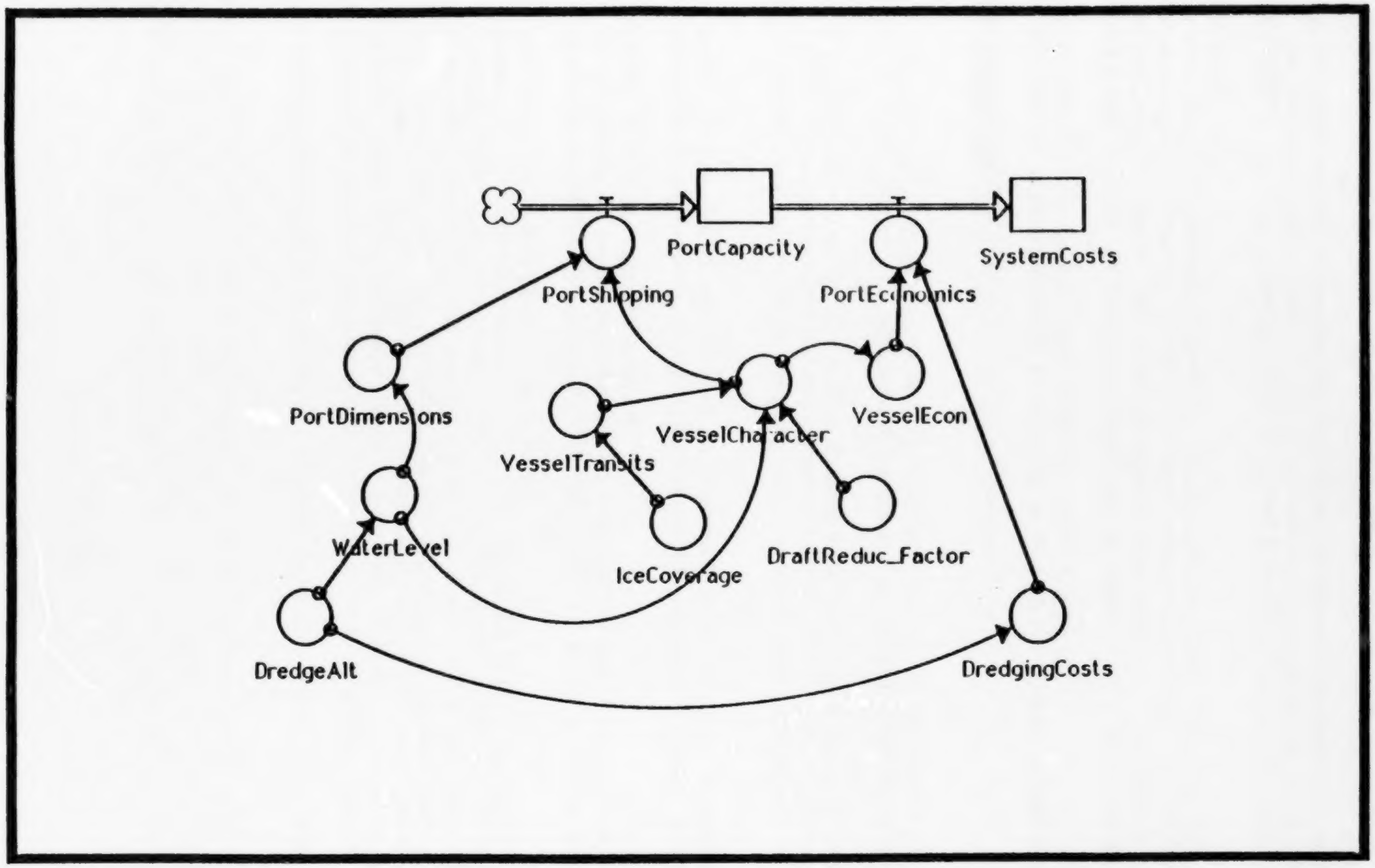
PortCapacity
SystemCosts
PortShipping
PortEconomics
PortDimensions
VesselTransits
VesselCharacter
VesselEcon
WaterLevel
IceCoverage
DraftReduc_Factor
DredgeAlt
DredgingCosts

Fig. 1. ECO Great Lakes Shipping Model.

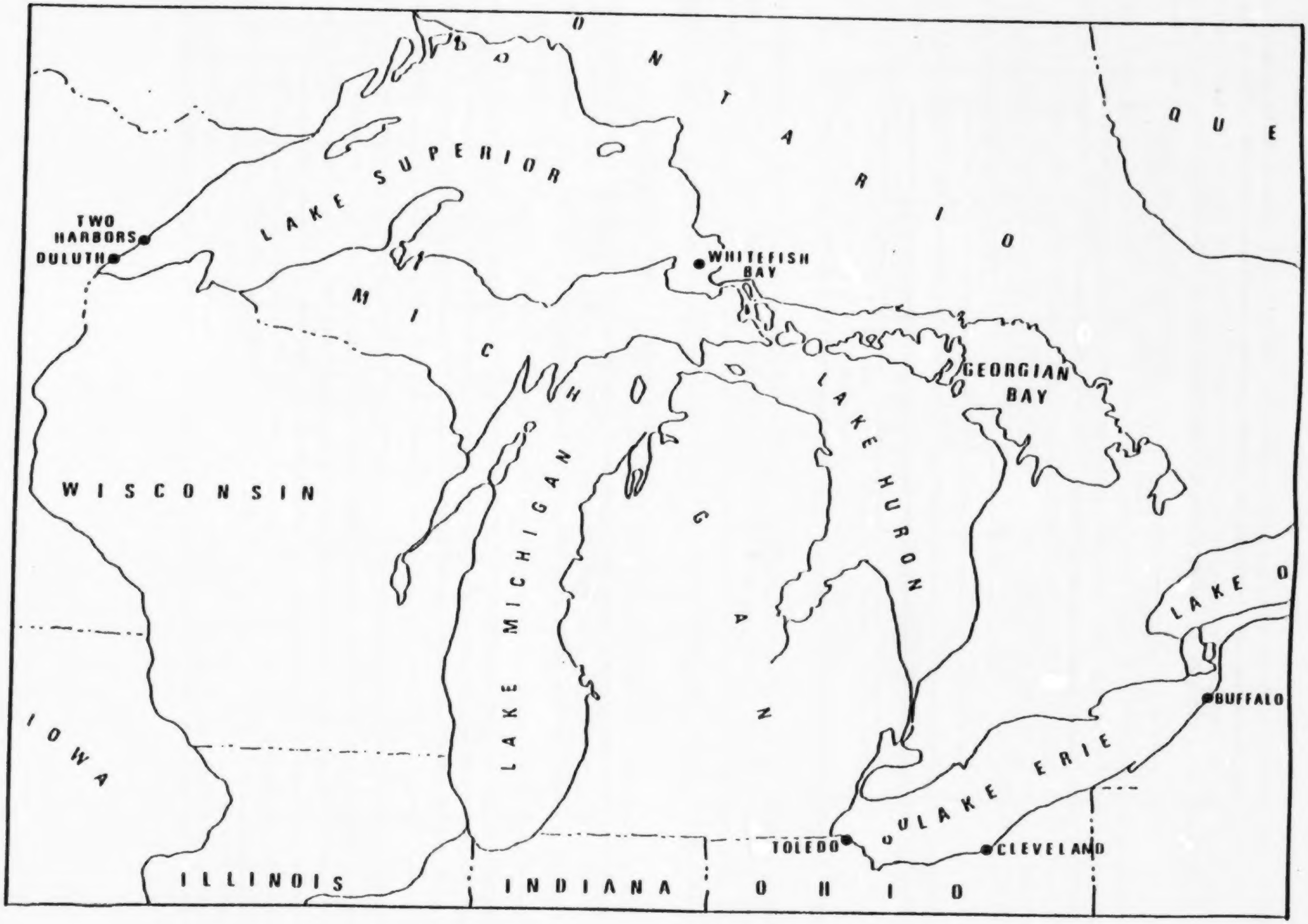
ONTARIO
QUE
LAKE SUPERIOR
TWO HARBORS
DULUTH
WHITEFISH BAY
MICHIGAN
GEORGIAN BAY
LAKE HURON
LAKE MICHIGAN
WISCONSIN
LAKE O
BUFFALO
LAKE ERIE
TOLEDO
CLEVELAND
IOWA
ILLINOIS
INDIANA
OHIO

Figure 2. Port area location.

Table 1. Physical characteristics of locations.

LOCATIONS	LIMITING CHANNEL DIMENSIONS (ft)	
	WIDTH	DEPTH
Two Harbors	600	28
Duluth	1100	28
Whitefish Bay	1300	28
Toledo	400	28
Cleveland	750	28
Buffalo	1050	27

TABLE 2. Average characteristics of vessel by class.

CLASS	LENGTH OVERALL (ft)	BREADTH (ft)	DEPTH (ft)	DRAFT (ft)	CARRYING CAPACITY (tons)
1	224	37	16	14	1,971
2	429	53	29	22	7,498
3	518	64	34	25	12,175
4	559	58	32	23	11,945
5	624	64	35	25	17,244
6	685	73	39	28	24,800
7	724	77	43	30	32,680
8	780	74	38	28	28,768
9	858	105	42	28	44,500
10	1003	105	53	31	70,142

and dividing by the number of tons carried. The value derived can be described by the term, "Required Freight Rate" or RFR. The derived RFR for each class of vessel affected by the climate change is given in Table 4. It is important to note that economies of scale are apparent in the shipping industry with the larger vessels with deeper draft carrying significantly more cargo at a lower cost per ton than vessels of lower classification. As the water levels drop, this advantage is reduced.

Cargo Capacity as a Function of Draft. A reduction in the water levels of the lakes will have an immediate effect on the cargo-carrying capacity of vessels transiting the lakes. All marine transportation systems are designed to operate at maximum drafts relative to the water depth. A decrease in the water depth will result in vessels reducing the amount of cargo that they carry on each voyage to reduce their draft. The reduction varies among vessels based on their design and normally is described by the amount of cargo in tons required to reduce the draft of the vessel by 1 inch. The cargo-carrying capacity of each class of vessels on the lakes for various drafts is given in Table 5.

Water Level Reduction. Three climate change scenarios have been used in the analysis. The scenarios are the following:

- o Goddard Institute for Space Studies (GISS), doubling of carbon dioxide ($2xCO_2$)
- o Oregon State University (OSU), doubling of carbon dioxide ($2xCO_2$)
- o Geophysical Fluid Dynamics Laboratory (GFDL), doubling of carbon dioxide $2xCO_2$).

The expected water levels due to the change in climate conditions, as simulated by the climate models, are shown in Table 6 for Lake Erie and Lake Superior. The lake level analysis for the GISS and OSU scenarios assumed that the current regulation plan for Lake Superior (Plan 1977-D) is in effect. In the GFDL scenario, the Lake Superior Regulation Plan was not used. Instead, it was assumed that over a 30-year period, total inflows in Lake Superior equal total outflows with no resultant change in lake level.

To fit within the parameters of the shipping model, a 1- and 2-foot reduction for Lake Superior and 2- and 3-foot reductions for Lake Erie were felt to be representative of the range of the climate models, and were used in the discussion of the shipping model to predict the results of change in the shipping industry. Where possible and appropriate, the discussion of the analysis does refer to the discrete scenarios to provide a feeling for the sensitivity of the analysis.

Ice Coverage Reduction. The simulations show a substantial effect on the ice coverage of the lakes in question. Figure 3 compares the duration of ice cover historically with the climate change scenarios for each location and indicates that the shipping season on the lakes, approximately 270 days, may be increased substantially due to climate change.

Dredging Costs. One alternative that planners may address in light of the water level reduction is the dredging of shipping channels to maintain those channels at their present depths. This action would maintain the status of shipping within the locations. Present dredging costs per cubic yard of dredged material for each location derived from maintenance dredging contracts currently in place are given in Table 7. These figures include the costs of maintaining present disposal sites that are used to contain contaminated material dredged from the confined harbor areas. The large amounts of dredging that may be required with reduced water levels may exceed the capacity of the existing sites. Costs for the creation of new disposal sites, and associated environmental protection issues, are not included in the costs in the table and may significantly increase the overall effective dredging cost.

Table 3. Vessel transits by draft.
(Number of transit)

DRAFT (ft)	LOCATION					
	Two Harbors	Duluth	Whitefish Bay	Toledo	Cleveland	Buffalo
28	107	275	594	26	48	0
27	42	157	251	93	9	7
26	9	292	149	78	202	9
25	1	22	41	14	175	7
24	2	71	79	141	97	22
23		74	92	164	44	24
22	1	38	90	155	71	34
21	1	34	77	103	32	23
20	1	26	67	119	59	13

Table 4. Required freight rate by class of vessel.

CLASS	ANNUAL COST ($/Year)	OPERATING COST PER DAY ($)	CARGO CAPACITY (Tons)	RFR ($/Ton)
3	2,132,000	18,613	10,000	17.04
4	2,303,000	22,804	14,000	14.39
5	2,473,000	23,607	17,250	12.21
6	2,814,000	21,845	24,800	8.36
7	2,985,000	22,370	30,500	7.05
8	3,496,000	23,506	32,600	7.19
9	4,264,000	28,690	44,500	6.43
10	5,373,000	28,449	60,020	5.18

Table 5. Ship cargo capacity at various channel depths.
(in tons)

CLASS	CHANNEL DEPTH (in feet)						
	22	[illegible]	24	25	26	27	28
3	10,200	10,800	11,400	12,000	12,000	12,000	12,000
4	11,340	12,000	12,000	12,000	12,000	12,000	12,000
5	14,370	15,330	16,290	17,250	17,250	17,250	17,250
6	16,160	17,600	19,040	20,480	21,920	23,360	24,800
7	20,420	22,100	23,780	25,460	27,140	28,820	30,500
8	21,800	23,600	25,400	27,200	29,000	30,800	32,600
9	31,540	33,700	35,860	38,020	40,180	42,340	44,500
10	44,900	47,420	49,940	52,490	54,980	57,500	60,020

Table 6. Predicted water level reduction.
(in feet)

	SIMULATION MODEL		
LAKE	OSU	GISS	GFDL
Lake Superior	1.28	1.41	N/A
Lake Erie	2.07	3.12	5.41

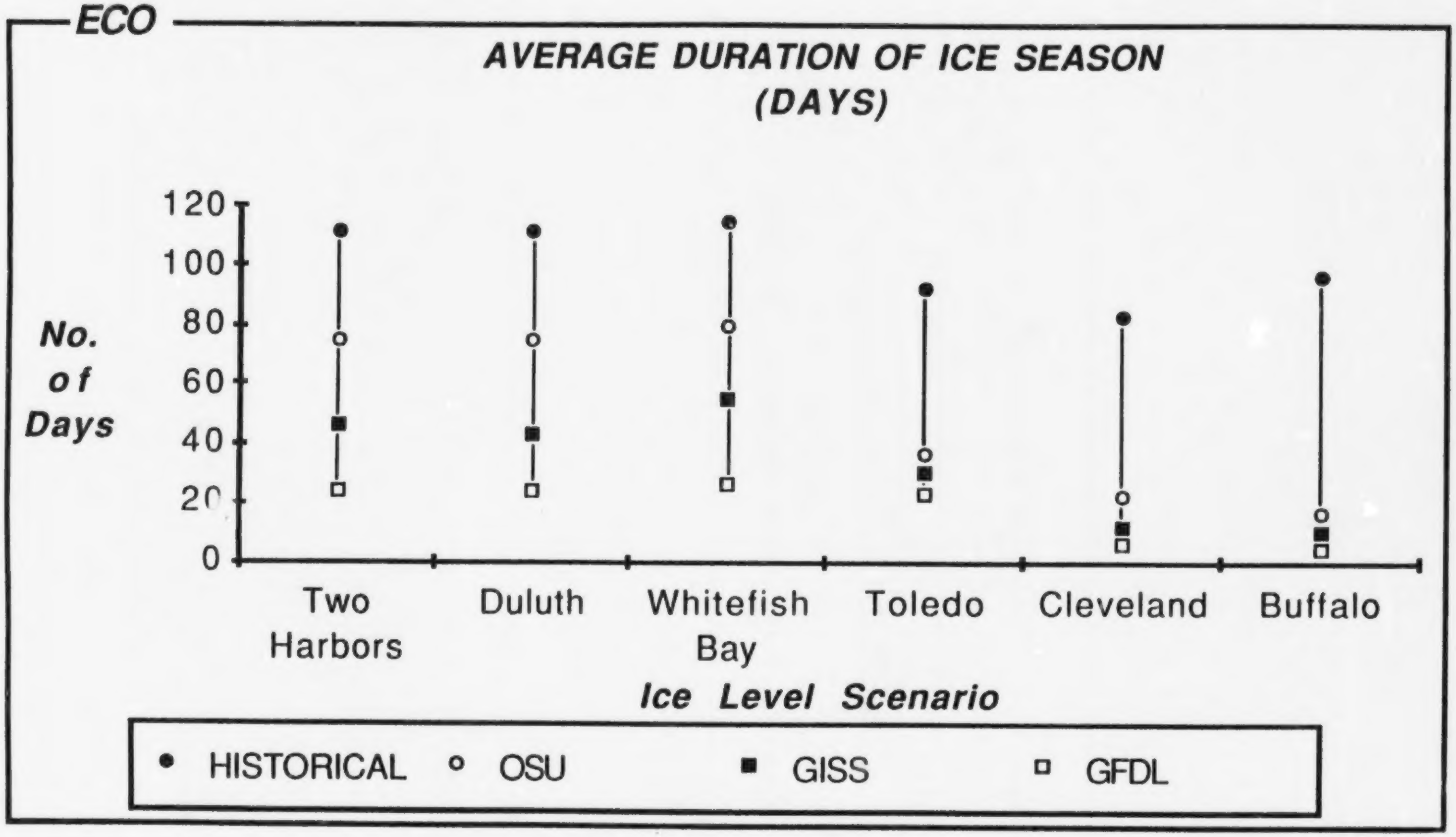

Fig. 3. Average season length in days as function of scenario.

Table 7. Dredging cost.
($ per cubic yard)

LOCATION	OPEN*	CONFINED**
BUFFALO	-	5.75
CLEVELAND	-	3.75
TOLEDO	1.75	2.70
WHITEFISH BAY	-	* * *
TWO HARBORS	-	6.00
DULUTH/ SUPERIOR	-	6.00

* Open - areas not requiring confined containment sites; such as open water dredged channels

** Confined - areas requiring confined containment sites for dredge spoil due to industrial contamination; such as enclosed harbors

*** Data for Whitefish Bay not estimated due to interaction with lock system

Source: U.S. Army Corps of Engineers

MODEL OPERATION

The ECO shipping model, Figure 1, was run for six different water levels -- the present system and water level reductions from 1- to 5-feet below the present system. The 5 foot reduction was used as the maximum reduction because it was the level at which the capacity demand of the most limited location could not be satisfied, even with a year-round, ice-free shipping season.

Using the existing mix of vessels and the existing cargo demand in each location, the model developed three measures of change that affect the shipping industry for each location:

- Change in the amount of cargo carried by the existing vessel mix in the present shipping season;
- Change in the cost of transporting the cargo due to lower cargo capacity per trip by affected vessels; and,
- Change in the number of days required to transport the cargo that is lost due to decreased carrying capacity per trip.

The reduction in ice coverage predicted by the climate models was then interrogated and integrated with the results of the shipping model. The model was run to evaluate the availability of additional shipping days due to reduced ice cover with the additional days required to ship the desired cargo in each location. The cost of transporting the cargo with the additional days was then computed for the locations. Finally, dredging costs were developed for the six locations and for the OSU, GISS, and GFDL scenarios.

CHAPTER 3

RESULTS

As previously stated, the model was run for 1- to 5-foot reductions in water levels. The results of those runs are given below for each location in terms of change in cargo-carrying capacity, transport cost per ton, and the days required to carry the cargo lost due to reduced carrying capacity. The explanatory labels on the tables in the following discussions show the water levels predicted by the three climate model simulations.

The probable increase in shipping season due to reduced ice coverage as a function of climate change scenario and the transport cost in an extended shipping season are given for each of the locations.

The dredging costs for each location are also presented for each of the three scenarios.

CHANGE AS A RESULT OF WATER LEVEL REDUCTION

Two Harbors

Figure 4 shows the results of the model for water level reductions for Two Harbors. For a 1- to 2-foot reduction in water level, cargo capacity for the location is reduced by 3.3 to 7.9%, with the model limit of 5-feet showing a decrease of 23.3%. The corresponding increase in transportation cost per ton is 3.4 to 8.5% at the 1- to 2-foot water level reduction, up to a maximum value at 5 feet of 30%. In order to transport the cargo lost due to water level reduction, 9 to 23 additional days would be required for 1- to 2-foot reductions, with a 5-foot reduction requiring 82 days.

Duluth/Superior

Figure 5 shows the results of the model for water level reductions for Duluth/Superior. For a 1- to 2-foot reduction in water level, cargo capacity for the location is reduced by 1.6 to 4.3%, with the model limit of 5-feet showing a decrease of 24.1%. The corresponding increase in transportation cost per ton is 1.6 to 4.1% at the 1- to 2-foot water level reduction, up to a maximum value at 5 feet of 29.4%. In order to transport the cargo lost due to water level reduction, 4 to 12 additional days would be required for 1- to 2-foot reductions, with a 5-foot reduction requiring 86 days.

Whitefish Bay

Figure 6 shows the results of the model for water level reductions for Whitefish Bay. For a 1- to 2-foot reduction in water level, cargo capacity for the location is reduced by 2.5 to 5.9%, with the model limit of 5-feet showing a decrease of 24.9%. The corresponding increase in transportation cost per ton is 2.5 to 6.3% at the 1- to 2-foot water level reduction, up to a maximum value at 5-feet of 31%. In order to transport the cargo lost due to water level reduction, 7 to 17 additional days would be required for 1- to 2-foot reductions, with a 5-foot reduction requiring 86 days.

Toledo

Figure 7 shows the results of the model for water level reductions for Toledo. For a 2- to 3-foot reduction in water level, cargo capacity for the location is reduced by 1.6 to 5.9%, with the model limit of 5-feet showing a decrease of 23.3%. The corresponding increase in transportation cost per ton is 1.6% to 5.1% at the 2- to 3-ft water level reduction, up to a maximum value at 5 feet of 26.8%. In order to transport the cargo lost due to water level reduction, 4 to 14 additional days would be required for 1- to 2-foot reductions, with a 5-foot reduction requiring 82 days.

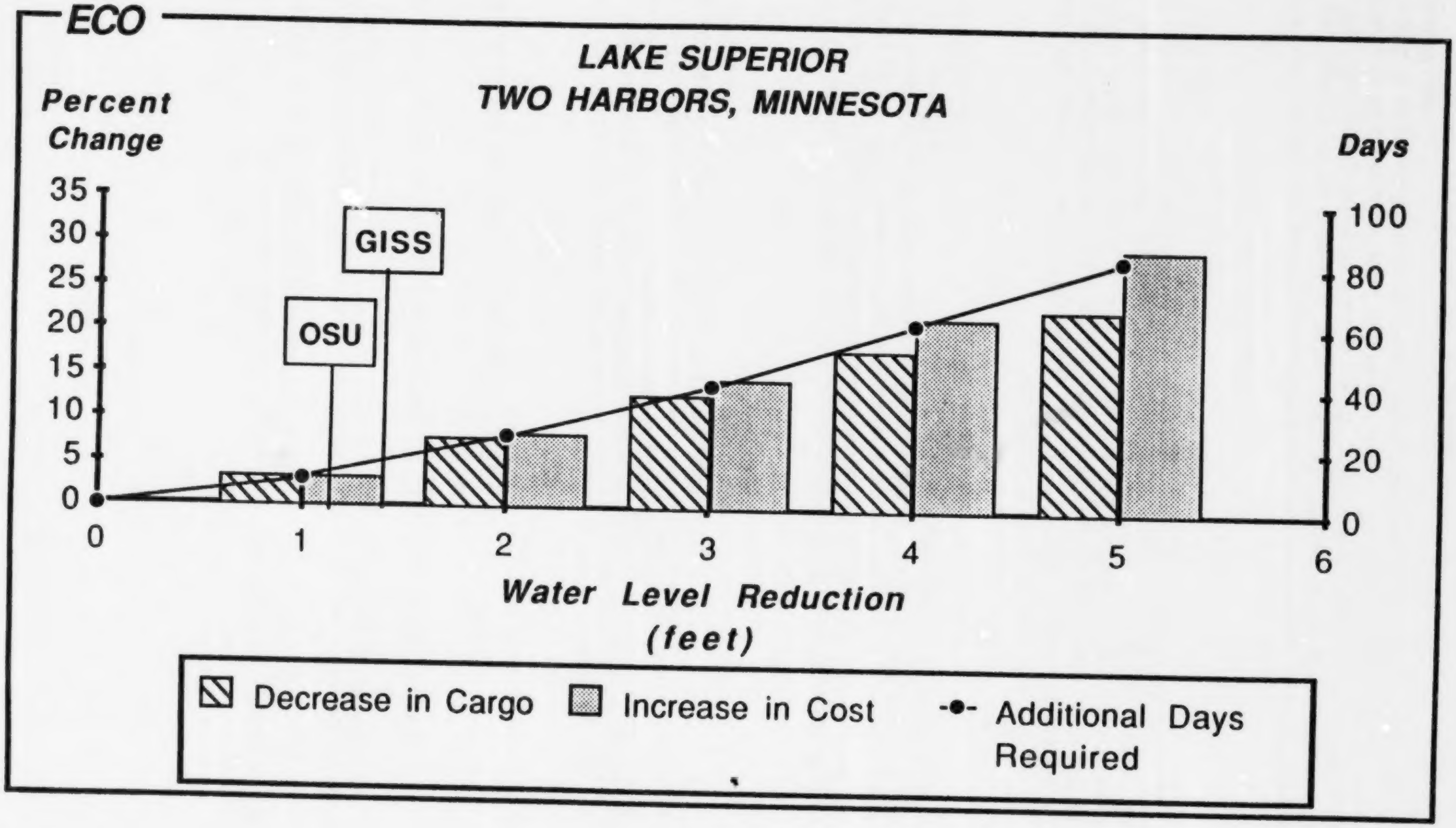

Fig. 4. Water level reduction model results.

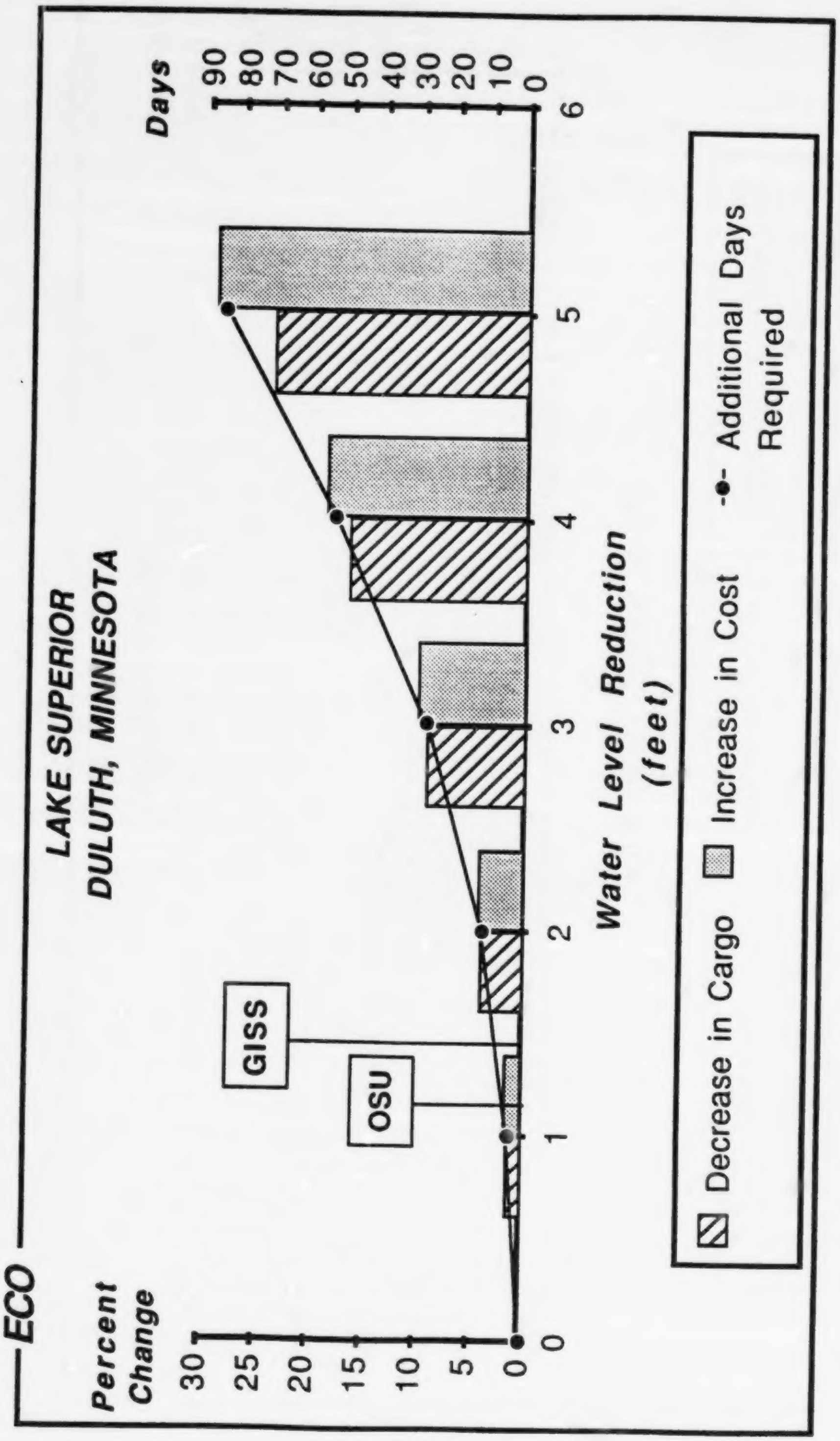

Fig. 5. Water level reduction model results.

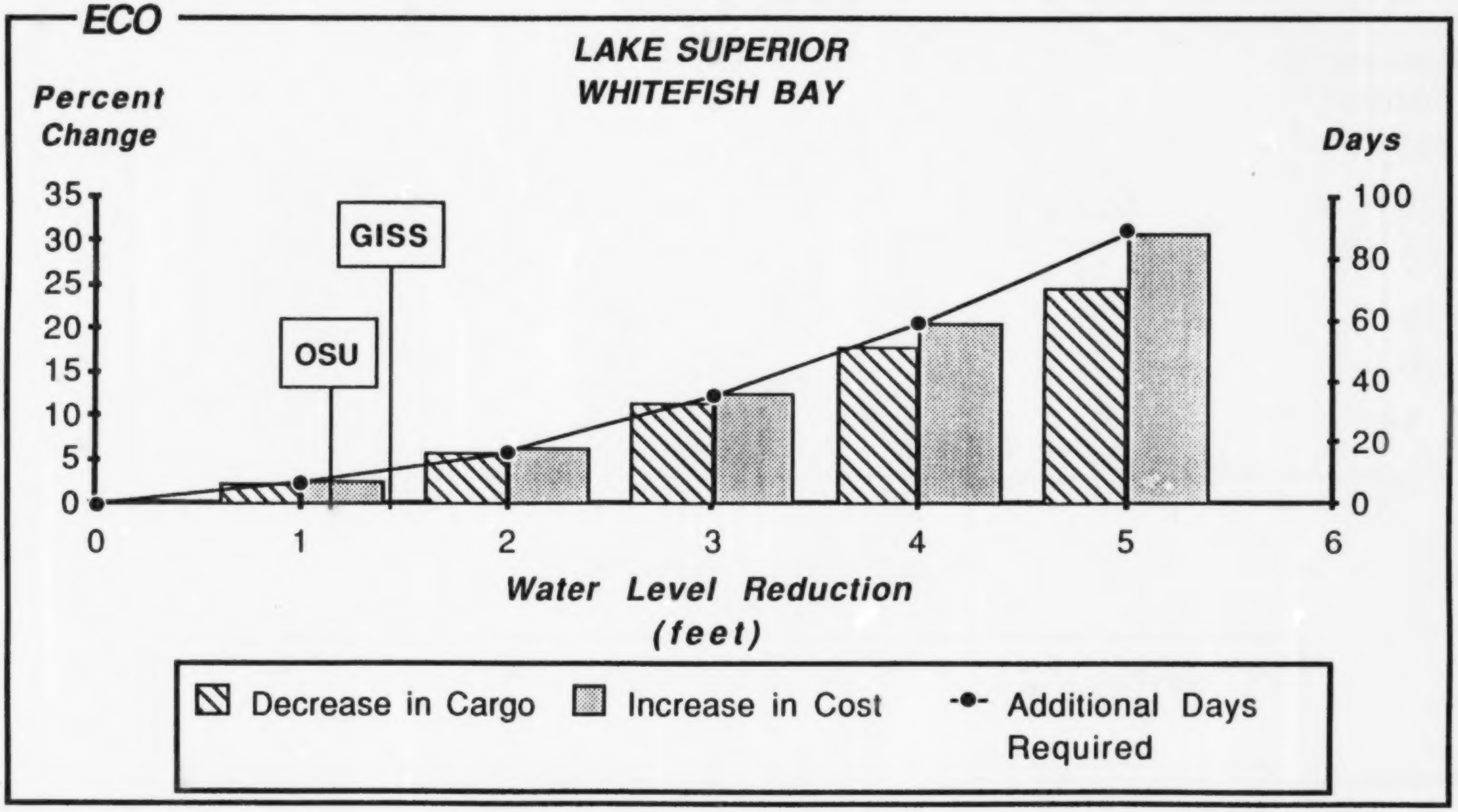

Fig. 6. Water level reduction model results.

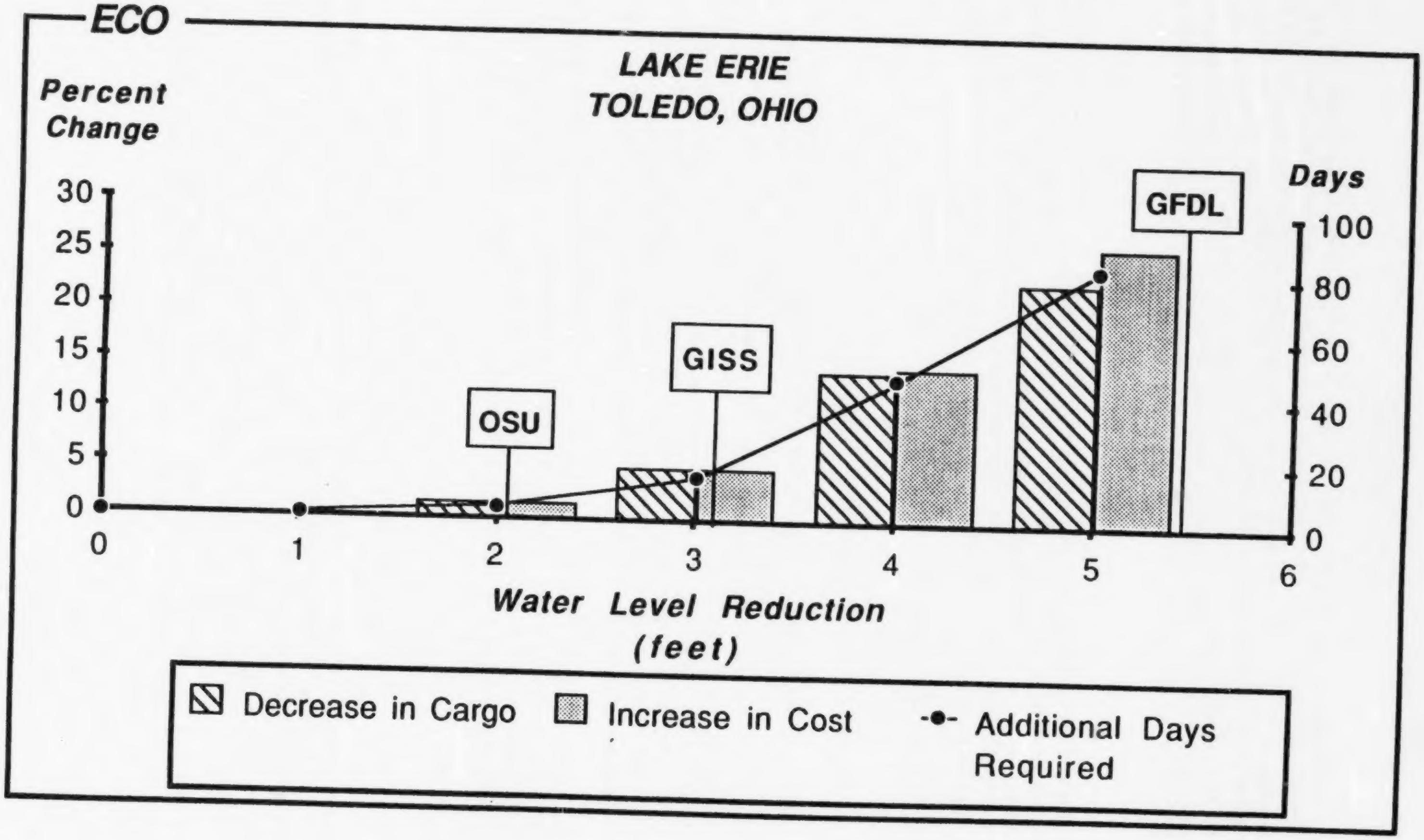

Fig. 7. Water level reduction model results.

Cleveland

Figure 8 shows the results of the model for water level reductions for Cleveland. For a 2- to 3-foot reduction in water level, cargo capacity for the location is reduced by 1.1 to 13.1%, with the model limit of 5 feet showing a decrease of 26.3%. The corresponding increase in transportation cost per ton is 1.1 to 13% at the 2- to 3-foot water level reduction, up to a maximum value at 5 feet of 31.7%. In order to transport the cargo lost due to water level reduction, 3 to 41 additional days would be required for 1- to 2-foot reductions, with a 5-ft reduction requiring 96 days. The significant difference between 2- and 3 feet can be attributed to the mix of vessels in the location, with vessels in the 26-foot range being prominent in this location; see Table 3.

Buffalo

Figure 9 shows the results of the model for water level reductions for Buffalo. For a 2- to 3-foot reduction in water level, cargo capacity for the location is reduced by 5.6 to 12.9%, with the model limit of 5 feet showing a decrease of 26.7%. The corresponding increase in transportation cost per ton is 5.4 to 13.1% at the 2- to 3-foot water level reduction, up to a maximum value at 5 feet of 32.9%. In order to transport the cargo lost due to water level reduction, 16 to 40 additional days would be required for 1- to 2-foot reductions, with a 5-foot reduction requiring 99 days. The significant difference between 2- and 3 feet can be attributed to the mix of vessels in the location, with vessels below the 25-foot range being prominent in this location; see Table 3.

CHANGE AS A RESULT OF ICE COVER REDUCTION

There are two effects on location shipping due to the reduction of ice cover. The first is the additional days available to transport the cargo demand for the location. The second is a corollary to the first, and results in a reduction in the cost per ton to transport the cargo. Under the reduced water level scenario, the locations are served by vessels carrying reduced cargo per voyage due to the reduction in water level with the result that less cargo is delivered at the same total cost as the present system. With a reduced ice cover, the shipping season is increased, and the same vessels can make additional voyages in a single season to, in most cases, deliver the total demanded cargo tonnage. The increased tonnage derived from the additional voyages is greater than the costs for additional operating days for those voyages. (See discussion on RFR earlier in analysis.)

Figures 10 through 12 show the shipping season days available as predicted by the various climate scenarios, compared with the number of days required to transport the individual location's total cargo demand for those scenarios interpolated from the data curves for water reduction alone. The effect of the reduced ice coverage on transportation cost per ton in each location is shown for each individual port.

Two Harbors

Comparison of the extended shipping season available due to reduced ice cover versus required shipping days due to reduced water levels shows that the cargo demand for Two Harbors can be satisfied under all climate change scenarios. Figure 13 shows that the cost for transporting the location cargo demand with reduced water levels and reduced ice coverage will be an [illegible] from the present system of 1.9% to 4.7% for a 1- to 2-foot reduction in water level.

Duluth/Superior

Comparison of the extended shipping season available due to reduced ice cover versus required shipping days due to reduced water levels shows that the cargo demand for Duluth/Superior can be satisfied under all climate change scenarios.

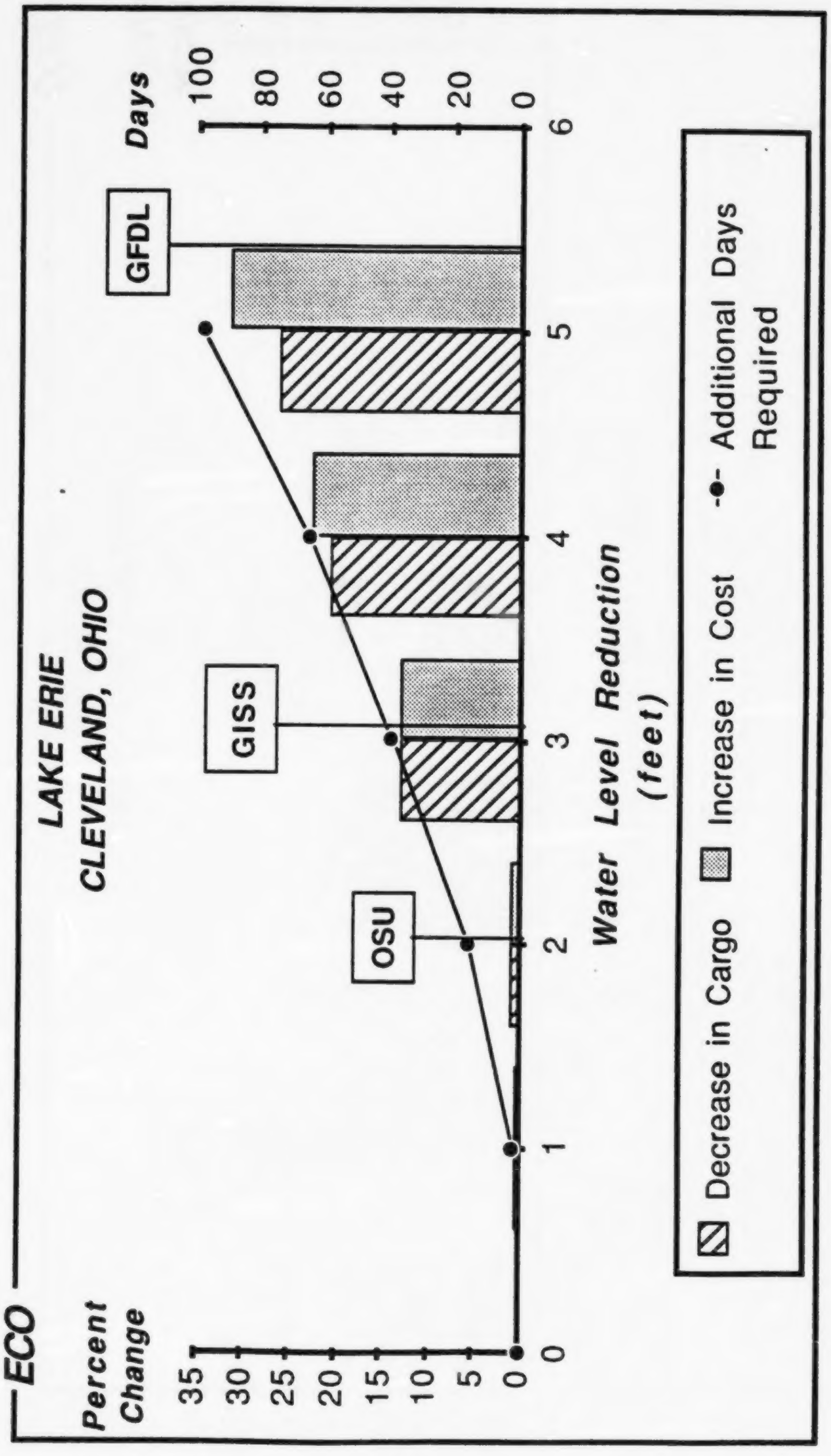

Fig. 8. Water level reduction model results.

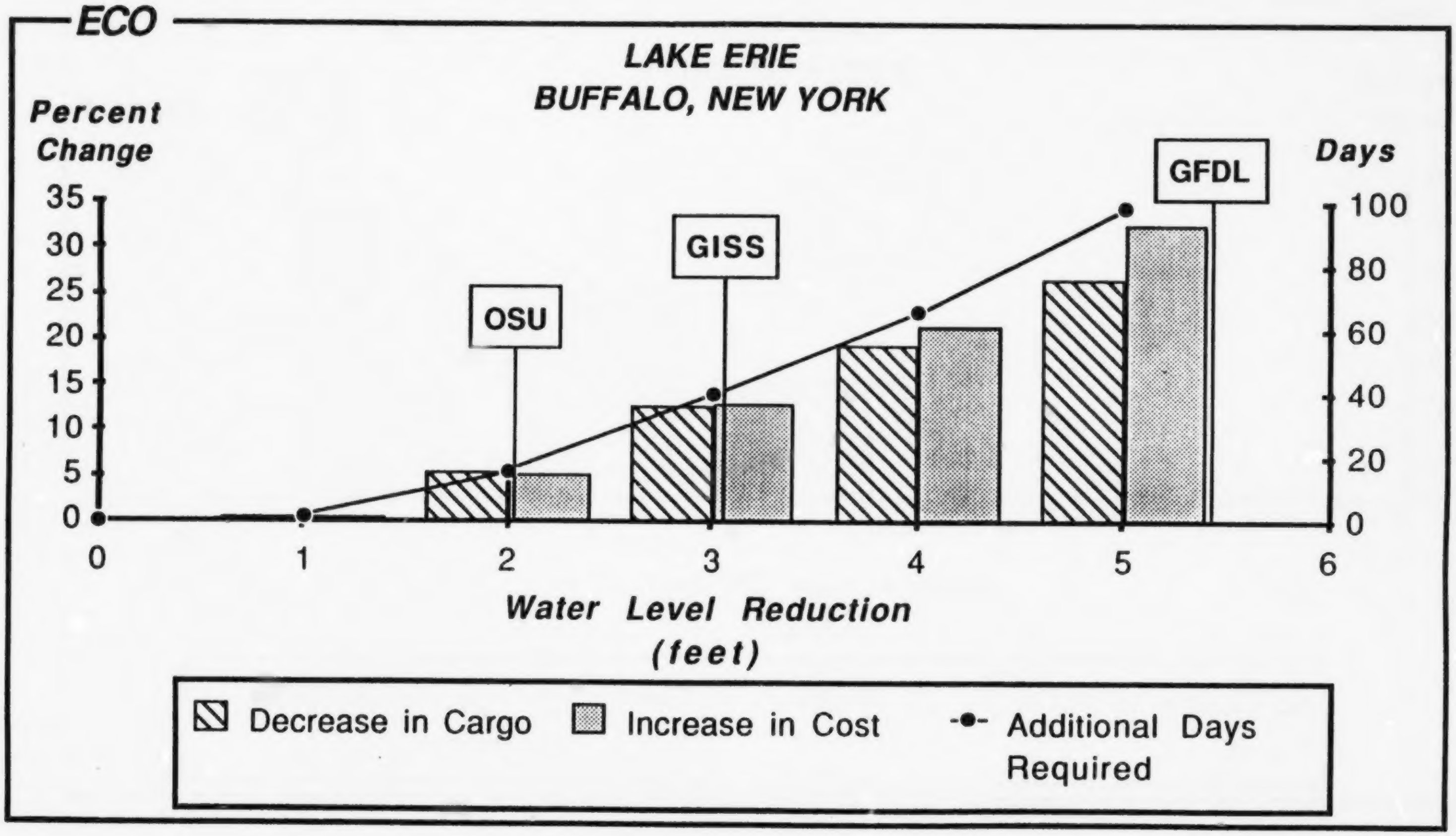

Fig. 9. Water level reduction model results.

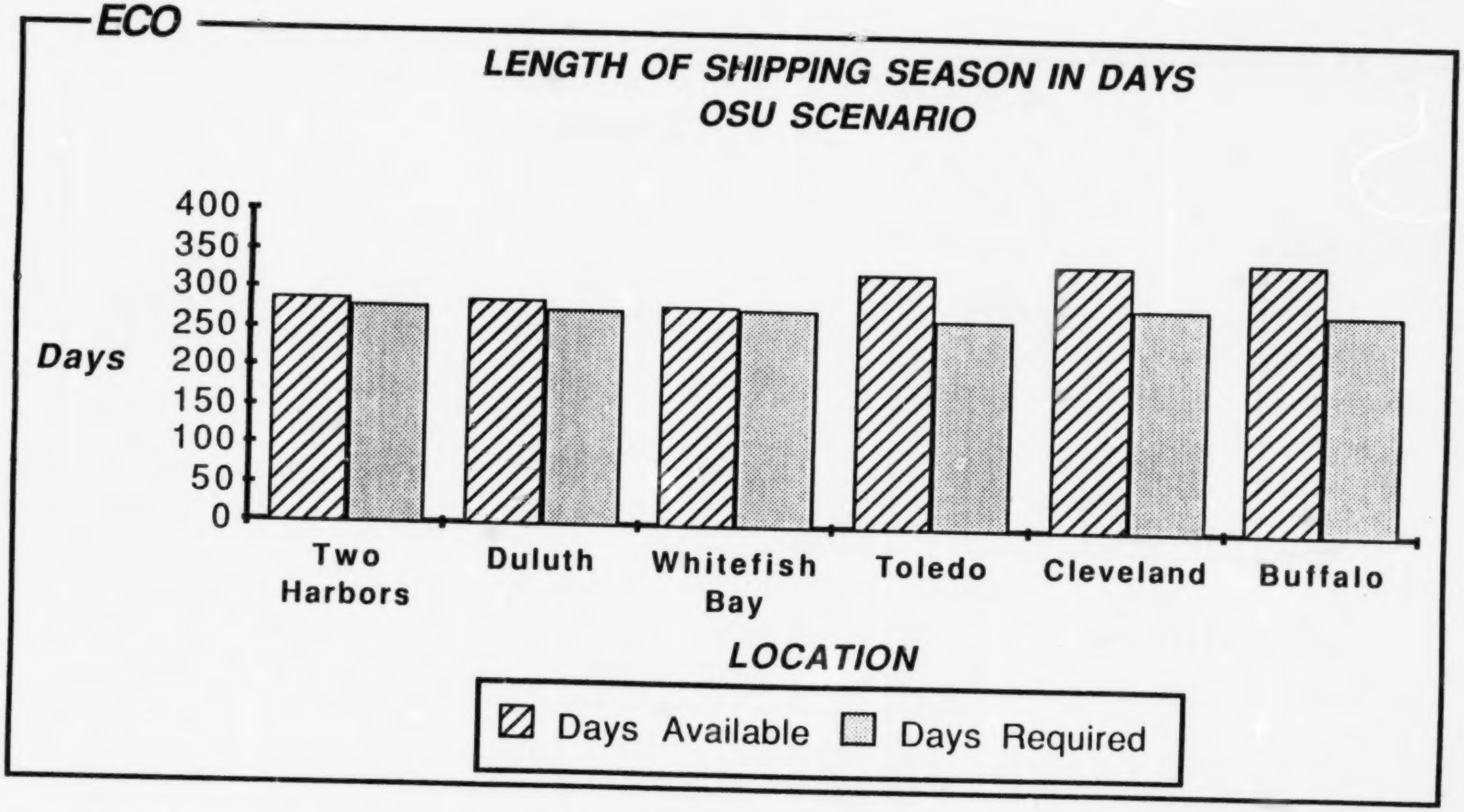

Fig. 10. Effect of ice cover reduction on shipping season length.

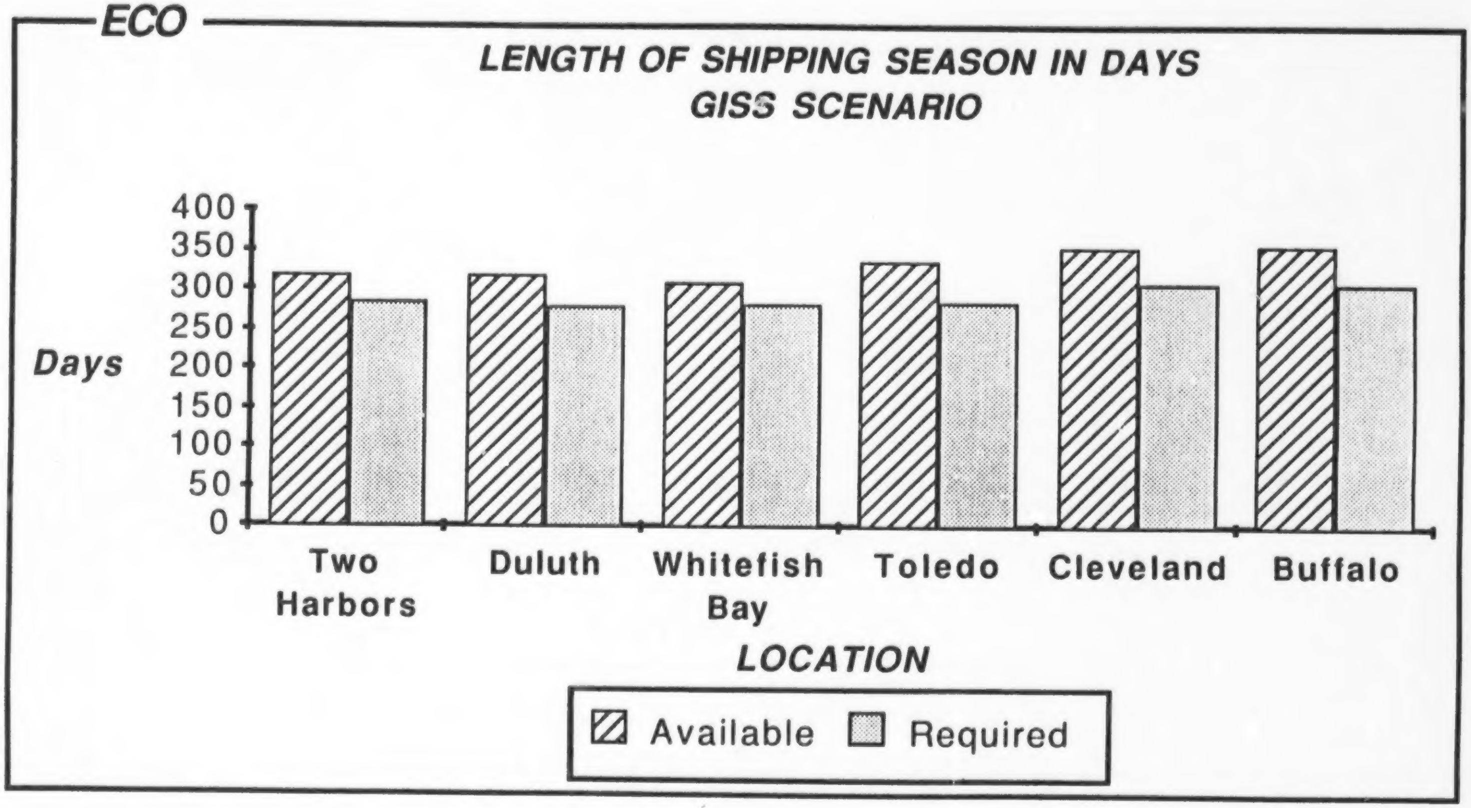

Fig. 11. Effect of ice cover reduction on shipping season length.

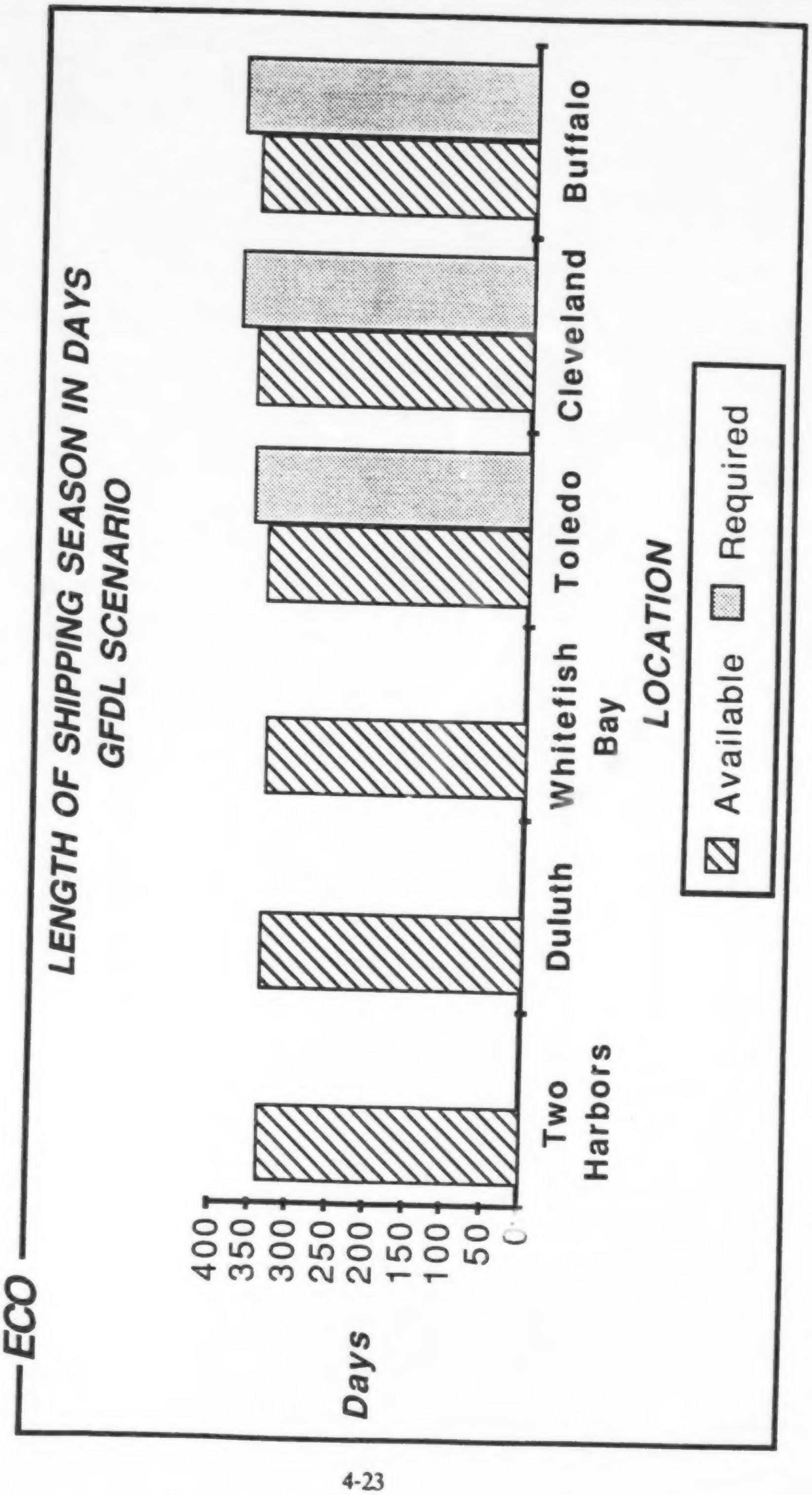

Fig. 12. Effect of ice cover reduction on shipping season length.

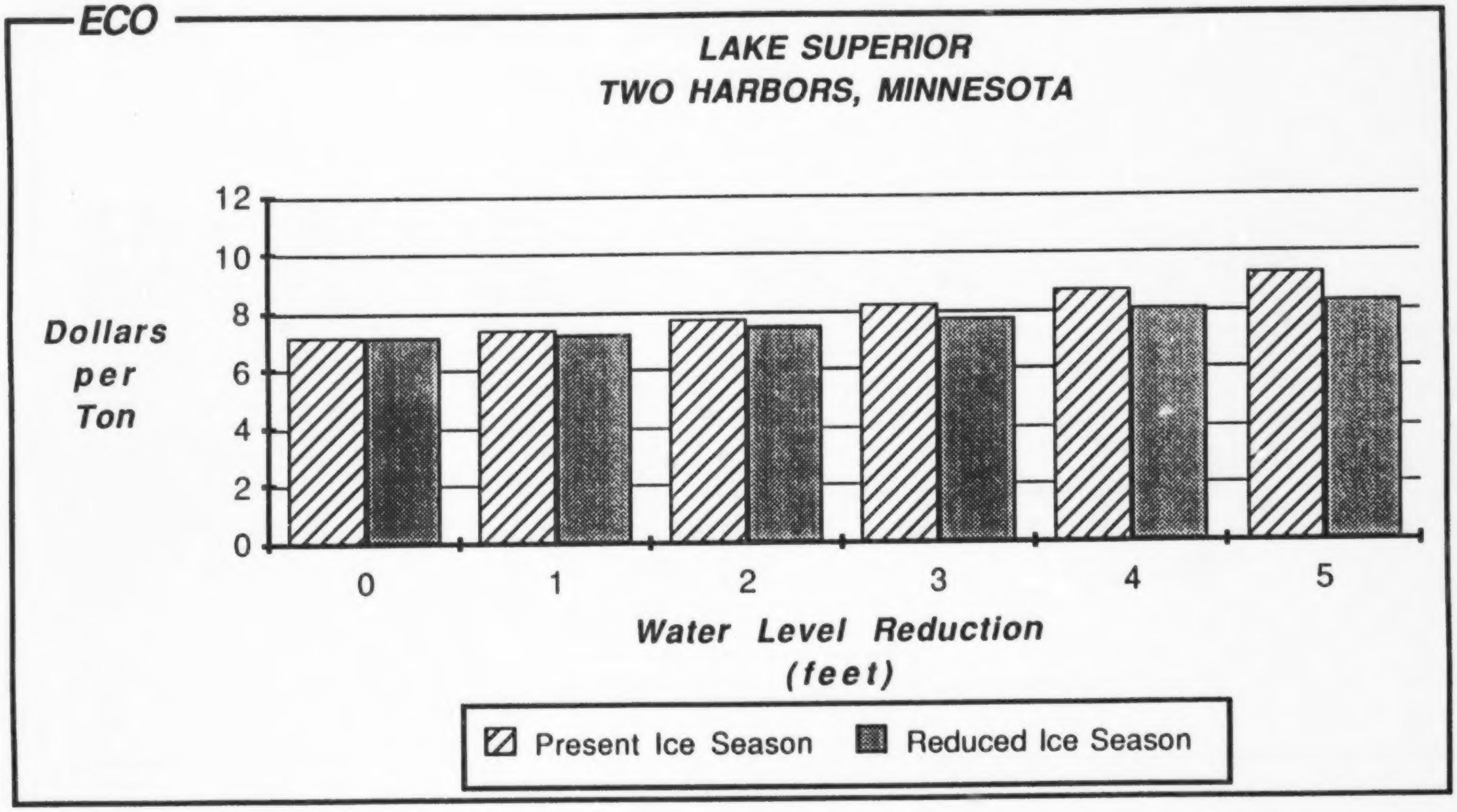

Fig. 13. Change in transportation cost due to reduced ice season.

Figure 14 shows that the cost for transporting the location cargo demand with reduced water levels and reduced ice coverage will be an increase from the present system of 1 to 2.3% for a 1- to 2-foot reduction in water level.

Whitefish Bay

Comparison of the extended shipping season available due to reduced ice cover versus required shipping days due to reduced water levels shows that the cargo demand for Whitefish Bay can be satisfied under all climate change scenarios. Figure 15 shows that the cost for transporting the location cargo demand with reduced water levels and reduced ice coverage will be an increase from the present system of 1.5% to 3.6% for a 1- to 2-foot reduction in water level.

Toledo

Comparison of the extended shipping season available due to reduced ice cover versus required shipping days due to reduced water levels shows that the cargo demand for Toledo can be satisfied under the OSU and GISS climate change scenarios but not under GFDL. Under the extreme water level reduction conditions of GFDL, the number of days required to fulfill the cargo demand exceeds the number of additional days available. The critical water reduction level for Toledo is 5 feet before the system can no longer satisfy the cargo demand. Figure 16 shows that the cost for transporting the location cargo demand with reduced water levels and reduced ice coverage will be an increase from the present system of 1 to 2.9% for a 2- to 3-foot reduction in water level.

Cleveland

Comparison of the extended shipping season available due to reduced ice cover versus required shipping days due to reduced water levels shows that the cargo demand for Cleveland can be satisfied under the OSU and GISS climate change scenarios but not under GFDL. Under the extreme water level reduction conditions of GFDL, the number of additional days required to fulfill the cargo demand exceeds the number of additional days available. The critical water reduction level for Cleveland is between 4- and 5 feet before the system can no longer satisfy the cargo demand. Figure 17 shows that the cost for transporting the location cargo demand with reduced water levels and reduced ice coverage will be an increase from the present system of 1 to 6.9% for a 2- to 3-foot reduction in water level.

Buffalo

Comparison of the extended shipping season available due to reduced ice cover versus required shipping days due to reduced water levels shows that the cargo demand for Buffalo can be satisfied under the OSU and GISS climate change scenarios but not under GFDL. Under the extreme water level reduction conditions of GFDL, the number of additional days required to fulfill the cargo demand exceeds the number of additional days available. The critical water reduction level for Buffalo is between 4 to 5 feet before the system can no longer satisfy the cargo demand. Figure 18 shows that the cost for transporting the location cargo demand with reduced water levels and reduced ice coverage will be an increase from the present system of 3 to 7.5% for a 2- to 3-foot reduction in water level.

DREDGING COSTS FOR ALL LOCATIONS

Using data from Tables 1 and 6 and the predicted water level reductions from the climate models, the costs to dredge existing location channels to maintain the present shipping patterns were ascertained. The costs for each of the climate models are given in Table 8. (Note: No dredging is required under the GFDL scenario for Lake Superior.) As stated earlier, these costs are probably understated as they do not include the development of new containment facilities that may be required for the increased volume of dredging that would be required under reduced water levels, nor do they account for the environmental assessments that may be required for the

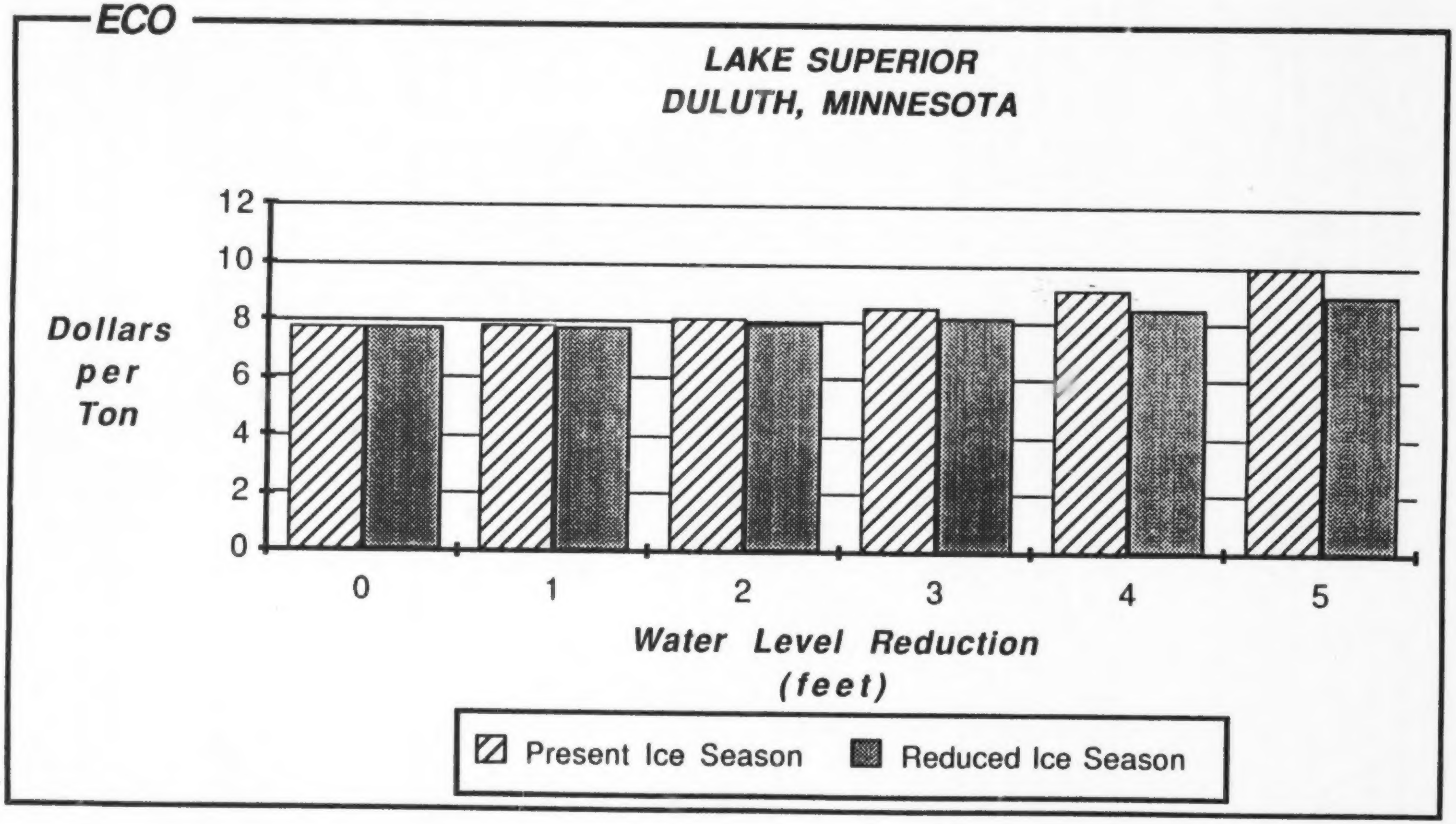

Fig. 14. Change in transportation cost due to reduced ice season.

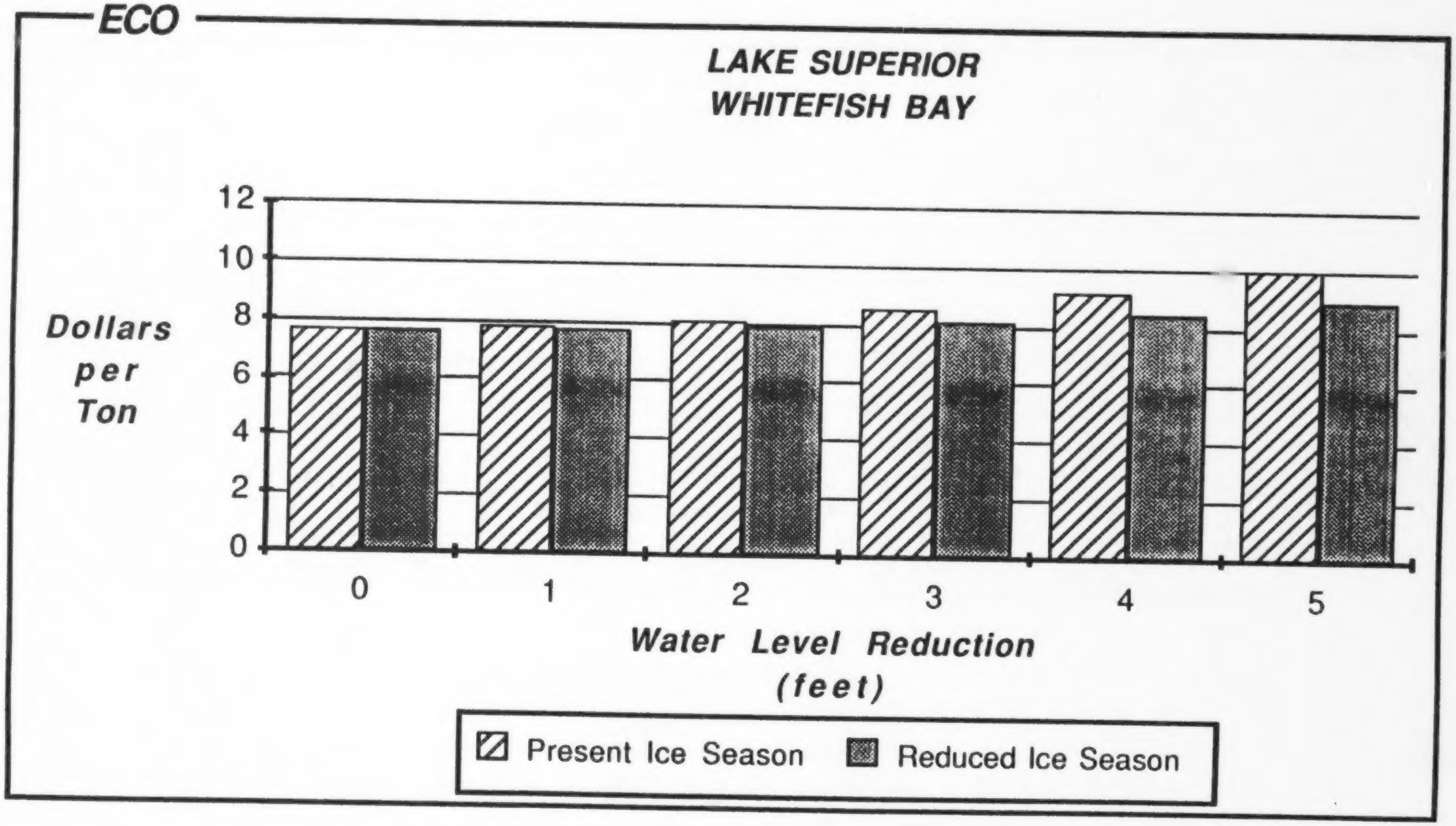

Fig. 15. Change in transportation cost due to reduced ice season.

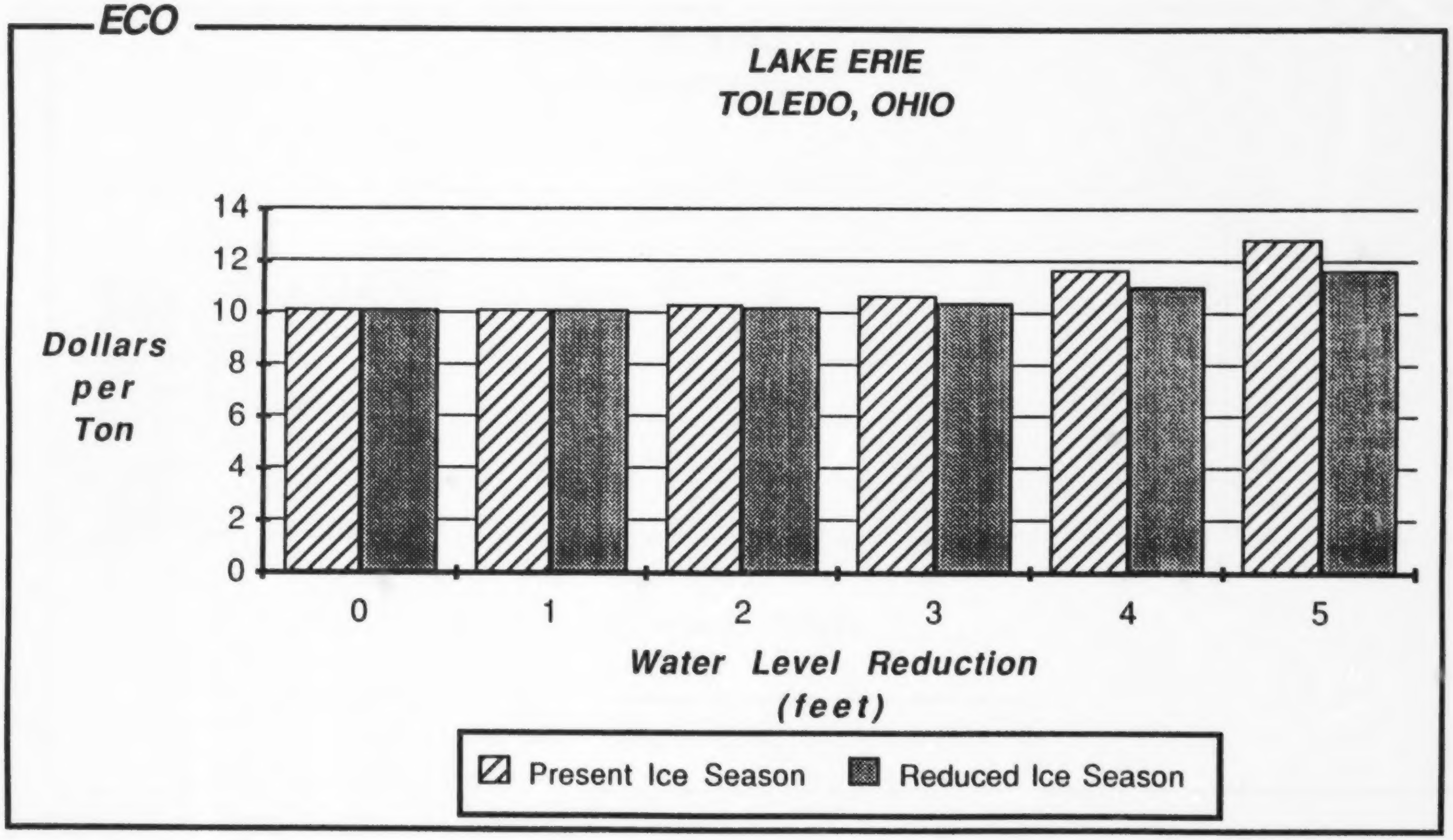

Fig. 16. Change in transportation cost due to reduced ice season.

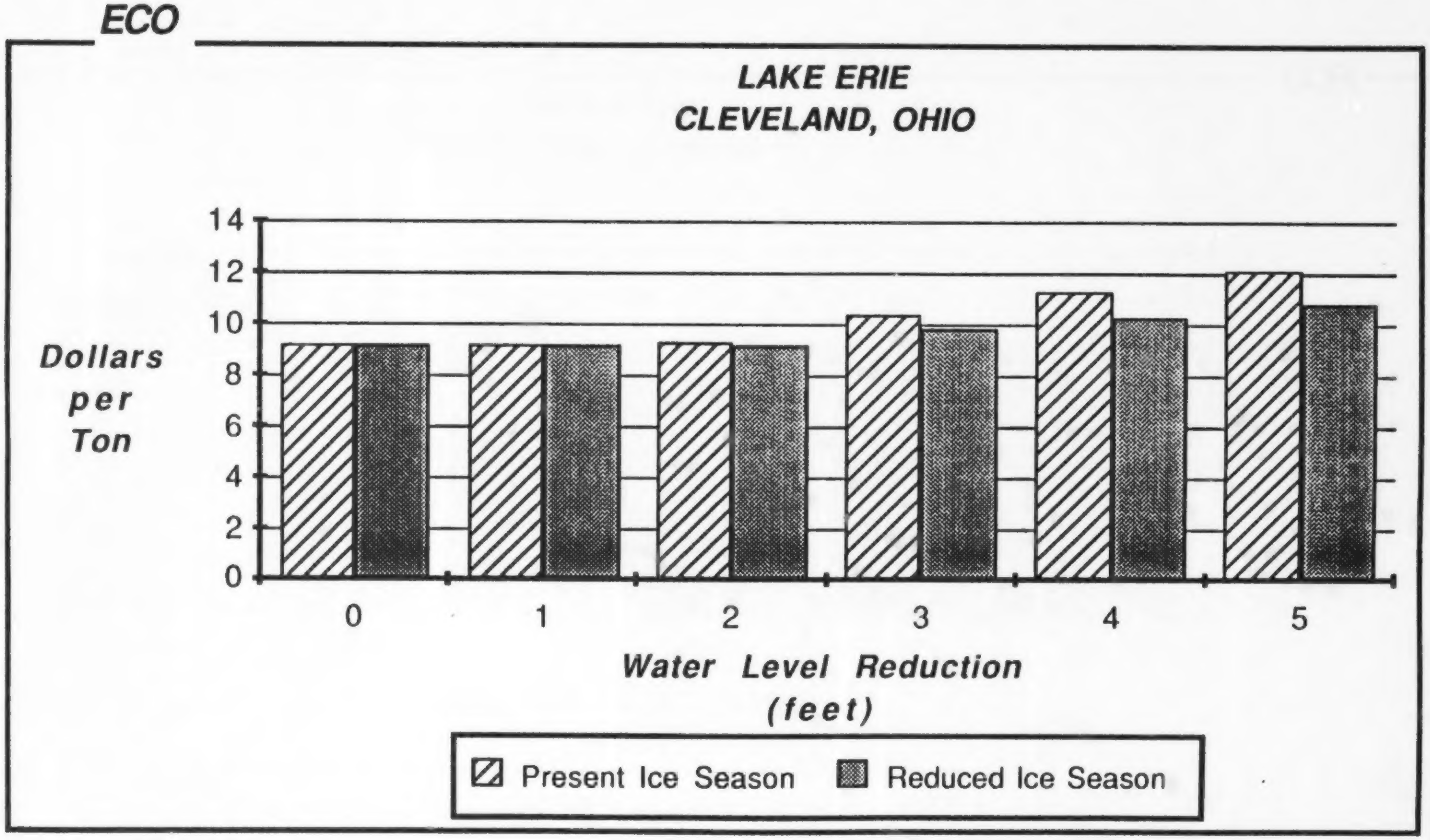

Fig. 17. Change in transportation cost due to reduced ice season.

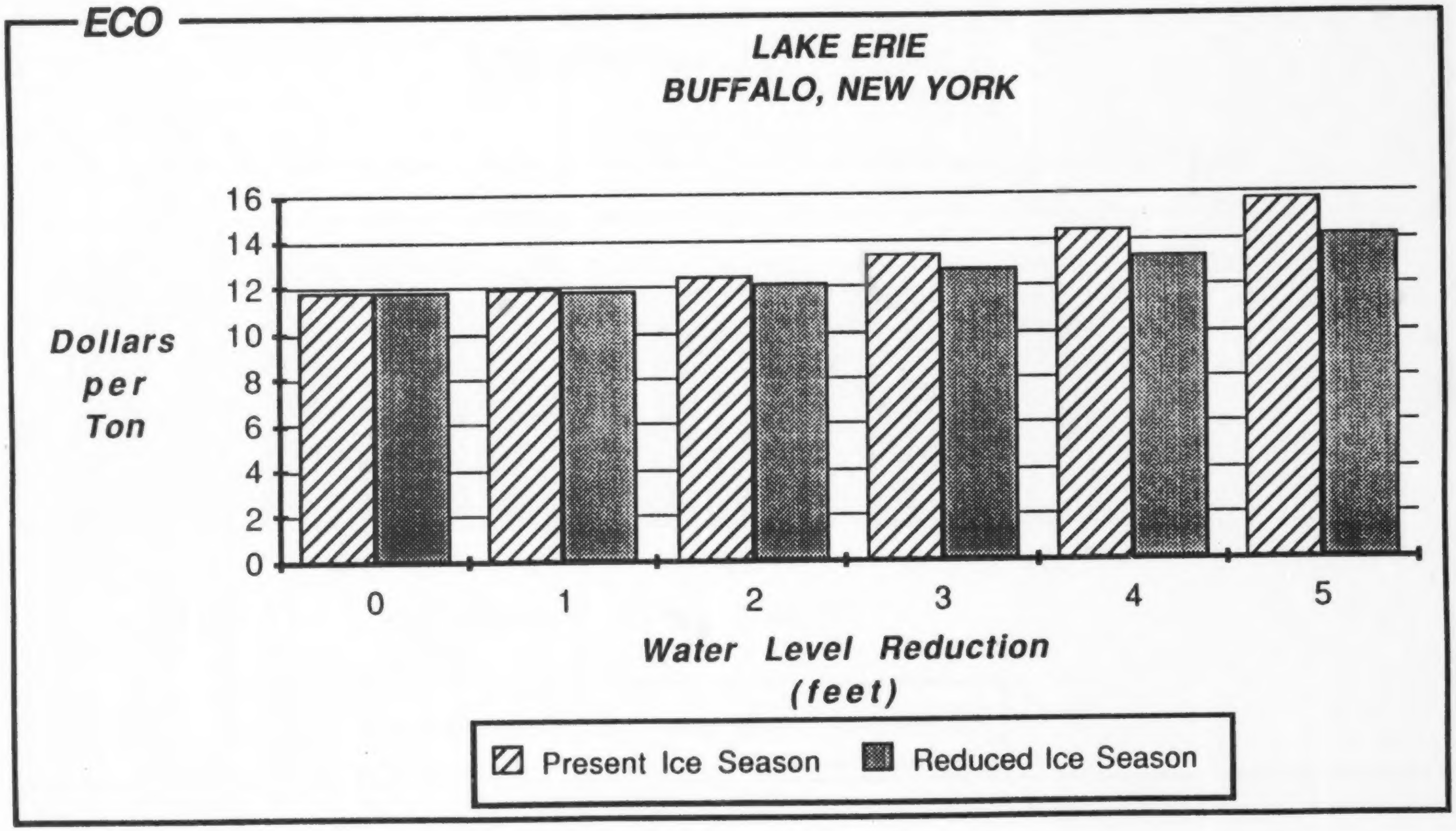

Fig. 18. Change in transportation cost due to reduced ice season.

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Table 8. Dredging cost.
(1987 dollars)

	WATER LEVEL		
LOCATION	OSU	GISS	GFDL
Buffalo	$10,800,000	$17,100,000	$30,900,000
Cleveland	$7,200,000	$10,900,000	$29,000,000
Toledo	$8,400,000	$12,600,000	$21,800,000
Duluth	$11,900,000	$13,100,000	N/A
Superior	$5,800,000	$6,400,000	N/A
Two Harbors	$300,000	$400,000	N/A

substantial increase in dredging activity. In addition, these costs do not include costs for other areas, such as the St. Marys River, which would require dredging and/or additional construction in order for the dredging of the individual locations to make economic sense.

CHAPTER 4

INTERPRETATIONS OF RESULTS

Climate changes in the midwestern region of the United States resulting in reduced water levels and ice coverage may have a significant impact on the transport of cargo by vessel on the Great Lakes.

The reduction in water levels may result in less cargo being carried per trip in the vessels affected, due to the need to reduce their draft. Correspondingly, the cost to transport per ton of cargo will increase. The magnitude of these changes in cargo carried and cost of the carriage per ton will vary according to the climate model used to estimate water level reduction, but may be in the range of an increased cost per ton carried of between 4 and 13% due to water level reduction isolated from any associated change in shipping season due to other warming effects such as reduced ice coverage.

The reduction in ice coverage will extend the shipping season. For all climate simulation models with the exception of GFDL, the availability of increased days exceeds the number of days required to ship cargo capacity lost due to reduced water levels. The locations in Lake Erie could not fulfill the cargo demand under the water level ice coverage reductions of the GFDL scenario.

The combined effect of reduced water levels and increased shipping season due to reduced ice coverage of the lakes will result in overall increases in cargo transportation costs of from 1% to 7.5% over present levels, or about half of the increases due to water level reduction without ice coverage reduction.

CHAPTER 5

LIMITATIONS OF RESULTS

There are two major limiting areas of the results considered here. The first is that the shipping model, as it has been applied to this discussion, treats each location independent from any other. This limitation becomes important when one considers that the climate models predict different changes in water levels and ice coverage from lake to lake. In reality, a vessel leaving Lake Superior usually delivers its cargo within the Great Lakes system. Therefore, the vessels in Lake Superior locations will not be affected as much by the changes in Lake Superior water levels as they will by changes in Lake Erie water levels, the destination of the cargo. These results tend to understate the changes that will take place in Lake Superior. Likewise, ice coverage duration in Lake Superior will dictate when vessels can transit from locations in Lake Superior and Lake Erie. Thus, the availability of ice-free waters in Lake Erie does not necessarily mean that shipping activity can occur if, at the same time, Lake Superior does have ship-confining ice.

The second area is that the model assumes, particularly in relation to dredging, that any limiting area or channel that the vessels may transit to the location does not affect the draft of the transiting vessel. However, the Great Lakes system does have two major areas, the St. Mary's and the St. Claire Rivers, that would be affected by the water level reduction and that cannot be bypassed by vessels in interlake commerce. The analysis of location dredging would realistically have to include both the dredging of these areas and the building of new locks to facilitate the transit of current vessels entering these systems at reduced water levels. Without the modification of these limiting areas, the availability of deep water at locations on wither side of these areas would be unnecessary and unused as vessels would have to reduce their drafts at any rate for the limiting area.

CHAPTER 6

IMPLICATIONS OF RESULTS

The results of the ECO Great Lakes Shipping Model show that the changes in water level and ice coverage on the Great Lakes due to changes predicted by various climate model scenarios will have an effect on Great Lakes shipping. The primary effect will be an increase in shipping costs due to reduced vessel carrying capacity. The reduction in ice coverage will extend the shipping season, and additional shipping days will be adequate, under most scenarios, to ship cargo capacity lost due to reduced water levels.

The increase in transportation costs may require that the maritime industry using the Great Lakes make substantial changes in their operations to maintain their competitive position. These changes may include increased support for dredging and construction projects to maintain shipping channels at present depths and/or may result in changing vessel construction technology or practices to transit reduced shipping channels.

REFERENCES

Assel, Raymond A. "Impact of Global Warming on Great Lakes Ice Cycles," Great Lakes Ice Cycle Data, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Ann Arbor, Michigan, (Unpublished paper).

ECOPORT, Engineering Computer Optecnomics, Inc., Annapolis, Maryland.

ECOSHIP, Engineering Computer Optecnomics, Inc., Annapolis, Maryland.

"Effects of Climatic Changes on the Laurentian Great Lakes Levels," Lake Hydrology Group, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Ann Arbor, Michigan, (Unpublished paper).

Final Interim Feasibility Report and Environmental Impact Statement on Great Lakes Connecting Channels and Harbors, U.S. Army Corps of Engineers, Detroit Division, North Central Division, Detroit, Michigan (March 1986).

Greenwood's Guide to Great Lakes Shipping, Freshwater Press, Cleveland, Ohio (April 1987).